STRATIFICATION IN OXIDATION PONDS

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by

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CERTIFICATE

This is to certify that this work on "Stratification in Oxidation Ponds" has been carried out under my supervision and that this has not been submitted elsewhere for a degree.

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STRATIFICATION IN OXIDATION PONDS

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This Research Report describes the experimental investigations conducted to find out whether some sort of stratification exists in the oxidation ponds.

A model of the oxidation pond was made out of 18 gauge glazed iron sheets. The depth of the pond and the rate of BOD feed were the two control variables. Usual chemical and biological parameters were determined when the pond reached a steady state under the given depth and rate of BOD feed. The two depths were 21 in. and 14 in., and the two rates of BOD feed were 50 lbs and 100 lbs/acre/day. The strength of feed sewage, which was the effluent from a septic tank for domestic waste in IIT Campus, was kept constant at BOD of 200 mg/l. The chemical and biological parameters were measured all through the depth of the pond by withdrawing samples from sampling points which were 3.5 in. centre to centre all along the depth starting from the pond level. The algae concentration was ~~made~~ determined photometrically at a predetermined

wavelength at which the absorbance difference between sewage and pond water with algae was maximum.

The steady state variation of alkalinity, organic-N and 5-D-BOD values of the samples centrifuged to remove algae from them showed that stratification exists in oxidation ponds. It consisted of three layers: upper one of lower alkalinity, higher organic-N and lower BOD; middle one of higher alkalinity and lower organic-N and lower one of lower alkalinity, higher organic-N and higher BOD. The BOD values varied gradually in between the two top and bottom layers. The steady state dissolved oxygen variation was linear perhaps because the two depths considered were not high enough and the light penetration was unobstructed.

The interesting finding was that algae production was increased when the detention time was decreased or when the feed volume was increased. This increase was almost linear. It may be recalled that such a situation exists within limits in the continuous growth cultures of bacteria and fungi. This finding, when confirmed, would be important from the design standpoint and algae harvesting.

Other conclusions ~~of interest~~ were that there was lower alkalinity in the top layers of the pond although the pH was high. This may, perhaps, be because of algae metabolism as they produce H^+ ions during photosynthesis.

There was no observable value of MPN at any depth in the pond even when the detention time was as small as 6.3 days in run IV. The nitrogen balance showed that a fair amount of denitrification was taking place in the pond and that it perhaps depends on the rate of BOD feed rather than the depth of the pond. With higher rate of BOD feed the amount of BOD satisfied anaerobically increased but the exact effect of depth and rate of feed on this was not very clear.

CHAPTER - I

INTRODUCTION

1.1 HISTORY AND DEVELOPMENT OF OXIDATION PONDS:

The deliberate addition of wastes to ponds as a means of waste disposal seems to have begun in prehistoric times and has continued until the present day. In ancient times in the Orient and Europe, many ponds have been built and operated to encourage algal growth by the addition of organic wastes, the algae serving as food for the various types of fish and the pond so operated greatly increasing the areal yield of fish. An interesting presentation of the history, technology and philosophy of such fish-culture-ponds from ancient times to the present has been given by Edministon(1). Sedgwick(3) has made frequent reference to the amazing purification of sewage when placed in ponds and lakes as compared to running streams. He observed that 'while dilution in running water and exposure to free oxygen did much, quiescence in ponds and lakes did far more'.

1.2 OXIDATION PONDS UNDER INDIAN CONDITIONS:

India, with her 80 per cent population living in smaller towns and villages, has a tremendous problem of waste disposal. Besides, her population is phenomenally increasing and there is also a rapid industrialization going on. One of the features concomittant to industrialization is organization and when people live in towns and cities the problem of waste treatment multiplies in importance. While there is a good case for the

prevention and control of water pollution, funds are hard to obtain in view of the more indirect benefits involved. All the money available for investment in our country at present is likely to be invested in multi-purpose irrigation schemes and in industry. Consequently, if water pollution control is to take a solid shape, the measures must necessarily be economical. In view of the high temperatures and abundant sunshine, 'oxidation pond' is likely to be the ideal method of treatment for domestic wastes for a majority of towns and small communities in India. It is so because when properly designed and operated oxidation ponds have a high degree of efficiency, are easier and economical to maintain and can be constructed easily and quickly at a low initial cost, and do not require skilled and trained operators to look after them. The waste does not require practically any pretreatment except grit removal and screening. The algae can be harvested, if a suitable economical method is found out, and used as a byproduct for the cattle feed or ultimately even for human consumption. The Central Public Health Engineering Research Institute, (CPHERI), Nagpur has brought out a brochure on oxidation ponds(4) in which many relevant details about pond design and construction are given. According to CPHERI, oxidation ponds are best suited for treatment and disposal of domestic wastes for populations in the range of 2,000 to 50,000. Its use is however, not limited to this range only. If conditions are favourable, it can meet the needs of bigger cities.

1.3 GENERAL STATUS OF OXIDATION PONDS:

Many papers are published discussing the general working and principles behind the operations of oxidation ponds and there was a symposium on this topic by CPHERI in Nagpur(5,6,7). It is observed that a well designed pond functions effectively without any odour and nuisance and produces stabilized effluent usually saturated with dissolved oxygen, and many of them are capable of and are actually supporting fish life. The treatment effected by an oxidation pond results from a complex symbiosis of bacteria and algae. The organics in the wastes are aerobically stabilized by bacteria to CO_2 and H_2O, and the algae through photosynthesis convert much of this CO_2 to algae cell material. Whereas the entering sewage solids are highly putrescible and hazardous to public health, the algal cells in the effluent are highly stable and have no pathogenic significance. The algae moreover constitute food for higher water animals like fish.

Anaerobic stabilization ponds are sometimes used in series preceding aerobic ponds(5). The purpose of such a combination is to complete in anaerobic ponds the putrefactive reactions of organic matter coming in and so reducing the organic load on the aerobic or facultative pond that is situated next. Sulphur and nitrogen compounds are simplified, oxygen depleted and the organic matter stabilized by bacterial oxidation and nitrification.

1.4 IMPORTANCE OF UNDERSTANDING POND PROCESSES:

It can be easily seen that oxidation pond is a complex system in which algal-bacterial symbiosis occurs and there is a delicate balance between the aerobic and anaerobic components of the total processes with respect to BOD load, detention time, depth and type of waste. The effective and efficient design of the pond would depend upon the clear understanding of all the parameters and factors that affect the pond processes. The quantitative assessment of the contribution of aerobic and anaerobic processes and the relative roles of the factors just mentioned are of paramount importance.

To put in summarized form,

(1) It is very important to understand the various pond processes that are associated with organic matter removal and nutrient removal.

(2) The effect of various physical and chemical parameters on the pond processes, both qualitatively and quantitatively, is very important for the design and operation of the pond.

(3) The knowledge of the above will enable an engineer to decide upon an optimum approach for the control and regulation of pond working in the field so as to achieve more efficient system of purification of wastes.

CHAPTER - II

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 INTRODUCTION:

The terms 'oxidation pond' or 'stabilization pond' or 'lagoon' are practically synonymous and applied to all bodies of water artificially created or employed with the intention of retaining sewage or industrial waste waters until the wastes are rendered stable and unobjectionable through biological decomposition. The effluent, then, could be disposed either by discharge into receiving waters or by seepage and evaporation.

A good and general review of oxidation pond literature is done by Fitzgerald et al(25). Babbit(5) in a recently written paper for CPHERI symposium has brought out clearly the various advantages and disadvantages of this method of waste treatment.

2.2 DIFFERENT TYPES OF OXIDATION PONDS:

The waste stabilization ponds are usually classified in literature into three types according to their depths. The deepest are termed the 'anaerobic lagoons' in which the anaerobic fermentation processes predominate. The incoming wastes soon consume most of the dissolved oxygen from the substantial portions of the lower layers of the pond. All these layers then become anaerobic and the degradation of organic matter in these layers proceeds anaerobically. There

is practically no aerobic zone in this type of ponds; the organic loadings are usually high and so are the detention times. Although there would be a considerable nuisance from malodorous gases from the anaerobiosis, the stabilization of the organic matter is really quite efficient per unit area of the pond. The anaerobic types of lagoons are well described by Parker et al(9). The depths of the anaerobic lagoons are generally of the order of 8 to 10 ft.

The second type of oxidation ponds are known as 'facultative ponds', in which anaerobic fermentation, aerobic oxidation and photosynthetic reduction processes occur at varying rates. Most of the oxidation ponds usually constructed in the field come under this category. The three processes that are named above constitute the main pond processes. The organic matter is stabilized both aerobically as well as anaerobically. The nutrients are usually removed in the form of growth of algae. The growth of algae depends upon carbon dioxide obtained either from aerobic bacterial oxidation of organic matter or from atmospheric absorption into the pond and on the nutrients that are obtained by bacterial degradation of waste, and on light energy that is required for photosynthesis. It could be seen that there are a number of interdependent factors on which the overall pond processes and their efficiency depends. Compared to anaerobic lagoons the facultative ponds have smaller depths (2 to 5 ft.), lower BOD loading rates and less BOD is actually removed per unit area of the ponds

when their performance is compared with high rate oxidation ponds discussed later. The facultative ponds generally have an upper aerobic zone and a lower anaerobic zone, a part of the incoming BOD load being handled by each. Since the anaerobic processes take longer time in stabilizing organic matter the pond requires longer detention periods for higher BOD removals as compared to completely aerobic systems. But at such higher detention times the aerobic and photosynthetic processes that ultimately influence the production of oxygen and its utilization for aerobic degradation of organic matter are not at their peak efficiencies. The facultative ponds are described by Caldwell(10), van Heuvelen and Svore(11), Hermann and Gloyna(12).

The third category is known as 'high rate oxidation ponds' in which bacterial oxidation and photosynthesis are balanced to yield completely aerobic stabilization, and if desired, a reclamable excess of algae. These types of ponds are described by Oswald and Gotaas(13).

Apart from the aerobic and anaerobic zones in the facultative ponds, there is a great probability that the pond processes like the BOD removal and algae metabolism which affect alkalinity, pH and nutrient concentration throughout pond would lead to some kind of stratification in the pond. There is, however, very little work done in this direction. Most of the work done so far considers the BOD removal, nutrient removal, etc. from the overall pond as studied from

the influent and effluent characteristics of these ponds. However, some of the work like that of Oswald(13, 14) indirectly has a considerable bearing on the pond processes as they occur throughout the pond.

2.3 EFFECTIVENESS IN LOWERING BOD:

The oxidation pond is an effective method of lowering BOD values of the wastes. The average values of BOD quoted by Fitzgerald et al (25) indicate that from 150 ppm of BOD, it could be lowered to 20 ppm when wastes are being stabilized in oxidation pond with a detention time of about 15 days and proper environment of light, temperature and absence of toxic materials.

2.4 POND LOADINGS:

The proper loading of stabilization ponds is obviously important because any purification system can become overloaded. In Europe the general figure of one acre per 1000 population is considered a safe limit, but loadings as high as 1800 people per acre of pond have given satisfactory results. In the National Research Council summary(26) the ponds studied had a loading of 25 to 50 lbs. per acre-ft. per day and satisfactory results were obtained. Detention periods were of the order of 20 to 30 days. Parker et al(9) made a study of loadings on the performance of ponds in Australia and found loadings of upto 67 lb. BOD per acre per day resulted in 90 to 100% purification. Loadings above these values resulted in diminished reduction in

BOD; loadings of 105 to 120 lbs. per acre per day resulting in only 80 to 85 lbs. per acre per day reduction. They suggest a load of 70 lbs. per acre per day for general use. It is obvious, therefore, that only vagge generalizations can be made as far as the loading of ponds is considered, because the differences in ponds, types of wastes, detention times and local environmental factors influence the effectiveness of oxidation ponds.

2.5 POND ALGAE:

The relation of algae to the process of BOD reduction in ponds has been investigated(15). Certain algae which grow in ponds, especially chlorella are capable of growth even in dark with organic compounds(27,28). However, numerous experiments have disproved this. Inasmuch as the growth of algae is controlled by temperature to some extent, the use of oxidation ponds in winter has been questioned. However, it has been found that the general efficiency of ponds for BOD removal is not greatly affected by temperature(25) studies in Denmark and North Dakota have indicated that frozen ponds also gave satisfactory treatment.

Oswald et al(29) discussed the relationship between depth, detention time, BOD removal, etc. concluding that the permissible loading factor is large in summer than in winter principally because the amount of light energy is greater, the light strikes the surface more directly and the temperature

is more favourable in summer. Neal and Hopkins(35) have found that there is little tendency for the BOD removal to vary, up and down, with the plankton density during most seasons.

2.6 OTHER FACTORS:

The literature shows that little work is done to determine the effect of detention time on BOD reduction taking place in ponds since few reports mention ponds run on an experimental basis with this factor varied. Parker et al(9) show that detention time in an anaerobic lagoon (first one in a series arrangement) should not be more than 5 days as the BOD reduction decreased with increased detention time. According to them, there is no effect with variation of detention time from 21.4 to 10.7 days on BOD reduction.

Allen(27) states that though larger facultative ponds with large detention times require little control they are not as efficient as small shallow ponds designed for more effective utilization of sunlight by algae. Such ponds are, however, more sensitive to environment and require greater degree of control. Oswald(29) maintains that the loading factor is lower for deeper ponds (3 ft.) than for a shallow pond (1.5 ft.) because the average light intensity is less throughout a large fraction of the volume of a deeper pond.

Recirculation has been shown to increase BOD removal only to a small degree but does not help in increasing photosynthetic efficiency of the ponds(14). Similarly light periodicity(percent of 24 hr period that light is continuously applied to a culture) of between 20 to 100% has little effect on the percentage of BOD removal. It was shown that with 40% or more of light periodicity the algae present produced 3 to 5 times the amount of oxygen required to satisfy the sewage BOD(25).

2.7 EFFECTIVENESS IN LOWERING BACTERIAL COUNTS:

A large number of studies quoted in (25) show that oxidation pond is very effective in lowering the bacterial count. In nearly all instances the bacterial counts have been lowered to less than 1% of the original concentration. The E.coli counts have been generally reduced from several hundred thousand to less than hundred per ml, and in one case where typhoid basteria were reduced from 41 per ml to nil.

2.8 EFFECTIVENESS IN REDUCING NUTRIENTS:

It has been seen that considerable amounts of plant nutrients are removed from the sewage by the action of oxidation pond. The nutrients are absorbed by algae for their growth and the nutrients are converted and concentrated into algal cell material. The ammonia-nitrogen is reduced from 15 or 40 ppm to less than 2 ppm in the pond effluent. Alongwith the 75 to 90% reduction in ammonia-nitrogen upto

60% of organic nitrogen is removed from the solution. Nitrate and nitrite nitrogen may increase but the amount present are normally insignificant compared to ammonia-nitrogen. It is also recorded that phosphorous levels were reduced by 96%. Most of this reduction is probably due to precipitation caused byn increased pH of the ponds rather than due to absorption by the algae. Potassium is reduced by 10 to 20%. Chloride concentrations as sewage passes through ponds are not consistent, sometimes increasing and other times decreasing. In general it can be said that algae will remove from solution the nutrients required for their growth; the algae concentration approaching about 400 mg of dry algae per litre of pond water(13).

2.9 ODOURS:

It has been found that(Oswald,13) during the two years of operation of a pilot plant under proper conditions no odours were observable, with the exception of a faint grassy one which is characteristic of the process. The observations included all night periods during which the pond was undergoing high loadings. When the ponds were overloaded in a deliberate attempt to breakdown the photosynthetic process foul odours were noticeable. These resulted principally from the anaerobic bottom sludges brought to the surface during stirring.Under proper operating conditions photosynthetic oxygenation is a process without objectionable odours.

2.10 INHIBITORS OF OXIDATION POND PROCESSES:

The inhibitor may be any biological or chemical agent interfering with the growth of algae in the pond. Although no direct study is made of this factor it can be said that such substances, if produced, do not attend high enough concentrations to interfere in the growth of algae. The algae of the genus chlamydomonas may be considered a contaminant as these grow swiftly covering the pond surface with foamy scum in one or two days. This scum prevents light from reaching the underlying strata and hence interrupts oxygen production. Fortunately such blooms are of short durations and they are easily skimmed from the pond surface.

2.11 ECONOMIC FACTORS:

The relative economies of conventional sewage treatment plants and waste-water oxidation ponds are dependent on local conditions. The pond construction requires more area than the conventional type of treatment plant. The conventional plants, however, would require the primary and secondary treatment facilities and the whole system would need proper maintenance. The ponds can also support fish life. Gloyna and Hermann(33) point out that 46% out of 188 ponds in Texas in 1957 supported fish life in varying degrees.

Another possible economic crop from oxidation ponds would be the algae grown in these ponds. Sewage grown algae do not seem to have as high a protein content as the same

species grown in other media(38), but they still can be considered a valuable protein source; but unlike fish, the harvesting of algae from the dilute suspensions found in oxidation ponds is very expensive operation and the problem is not completely solved yet(14). Much work has been done on the use of algae as a food source or a source of industrial raw material. Dried sewage grown algae is also found to be a good chicken feed(13,14).

2.12 POND PROCESSES:

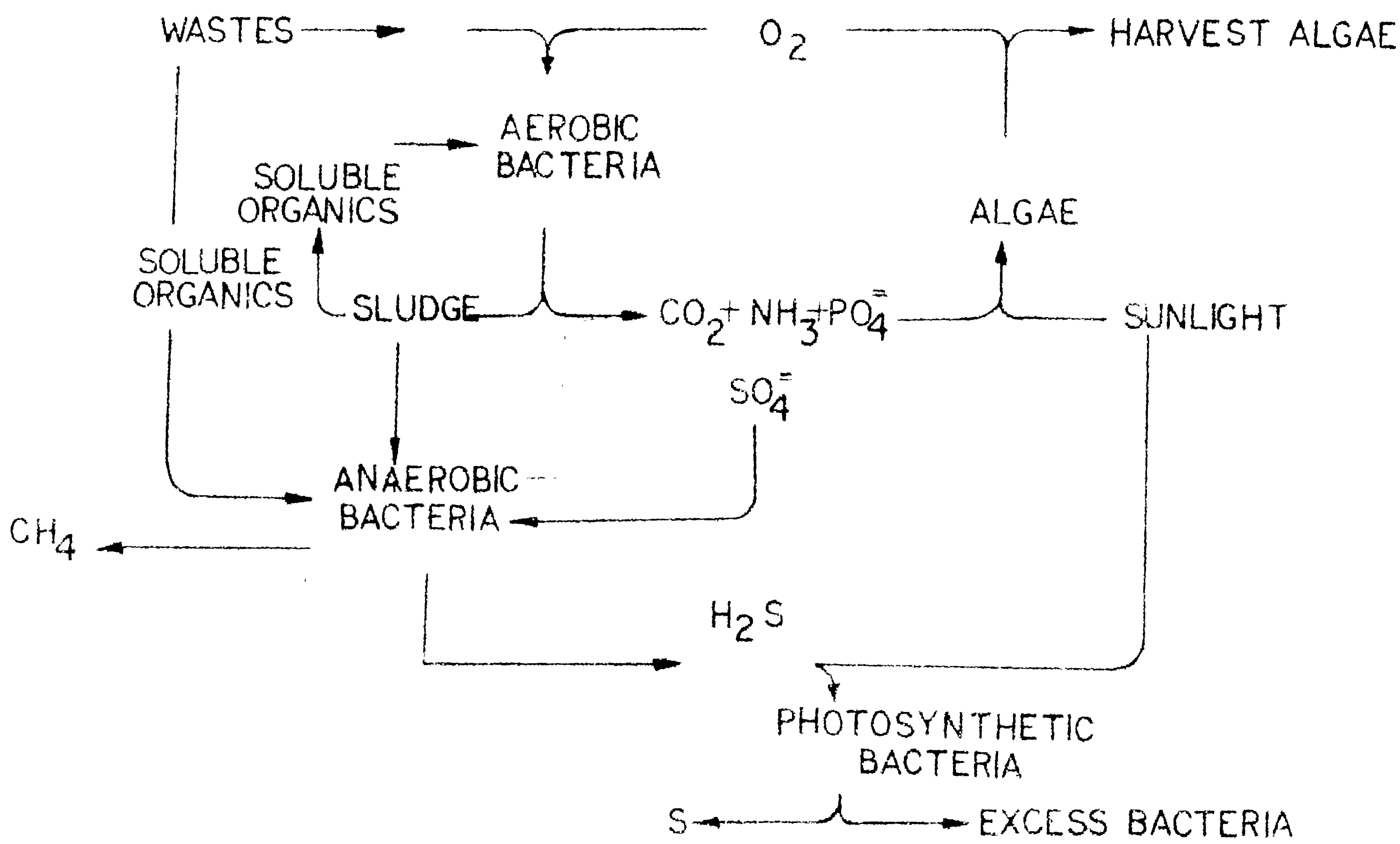
Pond processes are very important especially from the standpoint of the present research project. Quite a lot of work is done in this area by Oswald et al(13,14) and a few Research Project Reports were also published by them under the auspices of University of California, Berkeley, USA.

2.12.1 Types of Decomposition in Ponds:

The Fig. 2.1 by Oswald(14) explains schematically the overall reactions which commonly occur when wastes are continually added to the ponds. As the wastes come in quite a lot of suspended organic matter settles down within a matter of a few hours to form sludge, this process being called bioflocculation. The decomposition of the remaining matter is started by the bacteria, and the decomposition results in producing CO_2, NH_3, phosphates and other compounds. If the whole pond is aerobic then the sludge is also decomposed

FIG. 2·1

PROCESSES TAKING PLACE IN THE OXIDATION POND



aerobically and most of these compounds are formed. If little or no oxygen is available at the bottom, sludge may undergo partial decomposition, may increase in quantity without decomposition, or it may undergo partial or complete anaerobic decomposition. The anaerobic decomposition involves two stages. One, called acid fermentation utilizes oxygen from organic matter itself or from the oxygen-rich anions like sulfates, nitrates and gives rise to H_2, CO_2, H_2S and other odorous gases and to organic acids. The second stage involves, under favourable conditions, alkaline or methane fermentation as a result of which methane gas is formed together with some CO_2 and H_2. An important decrease in pond oxygen requirement occurs when organic matter is decomposed anaerobically.

Under favourable conditions of temperature, sunlight and nutrients, green algae usually grow in the top layers of the pond. The algae use CO_2, ammonia and phosphates resulting from bacterial decomposition to synthesize algal cell material and in so doing release O_2. This oxygen may become available for the oxidation of dissolved organics by bacteria. This cyclic process stabilizes the organic matter of the incoming wastes.

In another process shown in the Fig. 2.1, H_2S may be converted to elemental sulfur by photosynthetic bacteria. It is clear that for efficient working the pond would have

to be so designed as to make these processes work efficiently. The important processes in the overall pond working are sludge deposition, aerobic oxidation, photosynthetic oxygenation and anaerobic fermentation.

2.12.2 Sludge Deposition:

Sedimentation and bioflocculation are mainly responsible for the sludge deposition which occurs in ponds. However, autoflocculation and fecal deposition by invertebrates occasionally are significant.

2.12.3 Sedimentation and Bioflocculation:

It was found by Oswald(14) that about 90% of suspended solids in raw sewage were removed within about three days and 80% of dissolved solids in about 10 days by plain sedimentation. On the other hand, in oxidation ponds in which algal and bacterial growth had continued for sometime and in which the incoming waste water was mixed with pond contents, 85% of both suspended and the dissolved solids were deposited within four hours at the bottom of the pond. That is, the process of bioflocculation brings about a ten fold increase in the speed of formation and deposition of dissolved solids. The mechanism of bioflocculation is discussed at length by Lackey and Smith(16). The only important conditions for bioflocculation appear to be the presence of a rich and valid population of microorganisms, an ample supply of nutrients and sufficient time to develop a stable population. Bioflocculation is

accelerated as temperature is increased from 4 to 25° C, by the mixing action of waves or by mechanical recirculation, and probably by the movements of invertebrates which sometimes inhabit the ponds. Although bioflocculation due to growths of facultative heterotrophs is known to occur under anaerobic conditions, the presence of oxygen greatly increases the incidence of bioflocculation.

2.12.4 Autoflocculation:

Autoflocculation occurs in ponds containing dense algal population under special conditions. As described in several reports, e.g. (17), autoflocculation occurs as a result of an increase in temperature and the rising pH level of pond waters when the algal cultures are in vigorous state of growth during photosynthesis. The compounds like magnesium hydroxide, calcium sulfate and ammonium-calcium-phosphate become insoluble under these conditions and are precipitated. By enmeshing algal cells, detrius and bacteria the precipitates form floc particles which readily settle. Coliform removal is known to be enormously enhanced by such autoflocculation. Autoflocculation is always followed by a great decrease in dissolved oxygen because algae are carried into a zone of limited light and limited nutrients. The removal of hardness can also be t attributed to autoflocculation.

2.12.5 Fecal Deposition:

Invertebrates like rotifers, cladocera, ostracods and copepods are common in ponds, particularly during spring and fall. These organisms ingest algae and bacteria and are capable of rendering the pond virtually free of suspended solids other than themselves in a few days. However, only a small fraction of the bacteria and algae are digested by them, the remainder are simply added to the bottom sediments.

2.12.6 Aerobic Oxidation:

Disregarding phosphorous, sulfur and trace elements, the oxidation of organic matter in sewage in high rate ponds has been found experimentally to follow the reaction(19)

$$C_{11}H_{29}O_7N + 14\ O_2 + H^+ \longrightarrow 11\ CO_2 + 13\ H_2O + NH_4^+$$

Ammonia is rarely oxidized to nitrate in stabilization ponds because ammonia is either assimilated by algae, lost to the air or precipitated during periods of high pH before nitrification can become established. Although biological oxidation could ultimately result in virtually complete oxidation of available organic matter and the removal of first stage BOD, it does not proceed to completion in ordinary facultative ponds because the sludge which reaches the pond bottom is in a zone usually void of molecular oxygen. These deposits must either decompose anaerobically

or must be resuspended for aerobic oxidation. As the sewage entering the pond is devoid of any DO, only two sources of oxygen are available for aerobic oxidiation: atmospheric reaeration and photosynthesis.

2.12.7 <u>Atmospheric Reaeration</u>:

The oxygen deficit would develop in a pond that is heavily and continuously loaded with organic matter. The diffusion of oxygen from atmosphere into the pond would depend upon the magnitude of this deficit. According to Hutchinson(20), however, molecular diffusion as such plays a negligible role in reaeration of lakes. Reaeration due to wind action is a very difficult factor to be simulated in controlled experiments. The many formentations for oxygen diffusion based on oxygen deficit,really would not apply to oxygen ponds, as these show an oxygen deficit at night and supersaturation with oxygen during the day. The oxygen deficit which would make the diffusion of oxygen into ponds of any significance would have to be of such magnitude that it would make the pond considerably malodorous. Secondly, the atmospheric reaeration is of little significance in pond design because much less oxygen is taken up at night through reaeration than is lost during the day when the photosynthesis is vigorously taking place.

2.12.8 <u>Oxygen Production through Photosynthesis</u>:

Photosynthesis is a major source of oxygen for aerobic

oxidation in stabilization ponds. Oswald(14) has given the following reaction for the composition of algae(19) already known:

$$NH_4^+ + 7.6\ CO_2 + 17.7\ H_2O \longrightarrow C_7H_{8.1}O_{2.5}N_{1.0} + 7.6\ O_2$$
$$+ 15.2\ H_2O\ - 886\ Kcal.$$

About 3.68 calories are fixed for each mg of oxygen liberated and about 1.67 mg of oxygen are liberated for each mg of algae synthesized(13). The source of energy for this type of reaction is, of course, the sunlight.

The types of algae most active in oxidation ponds are the microscopic chlorophyceae, such as Chlorella and Scenedesmus or as in some cases Euglena and Chlamydomonas. Chlorella and Scenedesmus are extremely hardy. Individual cells are found to be viable after long periods of anaerobiosis, drying and freezing. Chlamydomonas and Euglena, on the other hand, die and decay readily under adverse conditions and hence may be less desirable in ponds which discharge in deep receiving bodies. The blue-green algae sometimes grow on sludge rafts at the surface and through their filaments lend added mechanical strength to the rafts. They also are found in suspended algal population.

The photosynthetic or light conversion efficiency is a function of light, time, nutrients and temperature. Oswald

in (14) gives the values of this efficiency computed by Oswald and is a useful guide in determining the potential efficiencies attainable in high rate ponds.

2.12.9 <u>Acid Forming Decomposition</u>:

The uncontrolled occurrance of acid formation in heavy sludge deposits built up over a period of time is the primary cause of objectionable odours which may be emitted by the stabilization ponds. This reaction produces CO_2, H_2, NH_3, organic acids and many odourous compounds such as indole and skatol, cadavarin and H_2S are produced in solution. The gases escape to atmosphere causing odour nuisance. Evolution of H_2S ordinarily is not a problem in oxidation ponds either because the compound dissociates into H^+ ion and HS^- ion when placed in solution of high pH existing in ponds or because it is oxidized in the presence of molecular oxygen. H_2S is almost entirely dissociated at pH 8.5 and more and the HS^- ion is odourless. H_2S can also be produced in the pond when under extreme anaerobic conditions the oxidation-reduction potential of the pond liquid may decrease such that the sulfate reducing bacteria become established and produce H_2S as a product of biooxidation, the reaction being stimulated by the high concentrations of sulfates in domestic waste-water.

Nitrite and nitrate reduction is not of importance in ponds because these anions ordinarily are not present in significant concentrations in domestic sewage nor are they formed from ammonia in appreciable concentrations in heavily loaded oxidation ponds. The algae quickly assimilate the ammonia before it can be oxidized to nitrites and nitrates.

2.12.10 Methane Fermentation:

The bottom deposits of oxidation pond are subjected to methane fermentation after acid forming stage when the conditions are favourable. These conditions are described in literature (24). The methane fermentation is a delicate process and many times may not be established in ponds if it is not well designed. According to Oswald(14) on an average methane, hydrogen and other combustible gases comprize more than 50% of the total gas produced, and about 1 lb. of BOD is reduced per 10 cft of gas evolved.

Methane fermentation is essential for the successful performance of the facultative oxidation ponds. Some pertinent facts about it would have a great bearing on the design of oxidation ponds. It is felt that indiscriminate sludge distribution would lead to a small thin layer of it to be deposited on the bottom and this would be exposed to the changing environment in the pond like the changes in DO, pH and temperature. Methane formers are not likely to be established under such conditions. Secondly, if the rate of sludge

deposition exceeds that of depletion by methane fermentation, the acid conditions would soon stop any further methane fermentation. If sludge blankets are permitted near the influent, by limiting recirculation, the warm entering sewage of almost uniform pH would form good environment. If these deposits are seeded with methane bacteria, they would thrive and a high reduction of BOD will be obtained. The pond also will be free of odours.

The pond processes as discussed in the previous pages, it is hoped, would prepare the background against which the results and discussions obtained in the present research project would be appreciated better.

CHAPTER - III

PROPOSED WORK, EXPERIMENTAL SET-UP & PROCEDURE

3.1 OBJECTIVES OF THE PRESENT STUDY:

The objectives of the present research project are to find out to what extent stratification, if any, in oxidation ponds into various layers takes place and to study the physical, chemical and biological parameters of the pond processes to obtain clear insight into them. It can be seen from the literature review that very few attempts have been made to study effects of various parameters on the pond processes, step by step and in detail, with respect to the depth of the pond under controlled laboratory conditions.

The objectives, therefore, can be spelt out as follows:

(1) A laboratory study, on the model of an oxidation pond, of the fluctuation of the dissolved oxygen content with respect to the depth of the oxidation pond, and its correlation with the important chemical and biological parameters under the controlled laboratory conditions.

(2) Assessment of the data obtained in the experimental study to see if any useful conclusions can be drawn for the successful and efficient operation of the oxidation ponds in the field.

3.2 MODE OF STUDY:

The assessment of the nature of variation of dissolved oxygen along the depth of the pond and other chemical and biochemical parameters to study stratification or otherwise in the pond would form the principal portion of the work. As far as the actual ponds in the field are concerned, they are subjected to many environmental factors that may modify the processes in ponds. These factors are as follows:

(a) effect of wind and the consequent mixing that it causes,

(b) effect of the variation of temperature in different seasons,

(c) effect of the mixing caused due to the movements of the vertebrates that also establish their residence in ponds,

(d) effect, if any, of the growth of weeds and other similar plants.

In the light of the above environmental factors, it is necessary to state that the present study is conducted under the following limiting conditions:

(1) No mixing of the contents of the pond was done to simulate the natural mixing occurring due to wind in the field.

(2) The incident light intensity on the surface of the pond is also kept constant. Four fluorescent tubes were fixed so as to be above the experimental model of the pond. The tubes were kept on all the twenty-four hours a day.

(3) There was no simulation for the mixing done by the vertebrates as in the case of field oxidation ponds.

It is proposed that the rate of feed of sewage to the experimental pond and the depth of the pond would be the two control variables.

(a) Two rates of feed are proposed - one, 50 lbs. per acre per day of BOD load (56 kg/hectare/day) and second, 100 lbs. per acre per day of BOD load (112 kg/hectare/day).

(b) Two depths of the pond are proposed - one, 21 inches (53.40 cms) and the other, 14 inches (35.5 cms).

These values of the feed and the depths are arbitrarily fixed after the study of relevant literature. Actually the stratification, if it takes place in the pond, can be firmly established only after performing experimental work with various depths of ponds and feed rates, etc. However, to finish the work within a reasonable time, the above two values of the control variables were adopted.

3.3 EXPERIMENTAL PARAMETERS:

Any combination of chemical and biological system

takes its own time to come to a steady state. In the present work, as outlined earlier, the parameters are to be determined only when the oxidation pond attains a steady state with respect to the pond processes under the given set of conditions. The steady state can be recognized by a steady pattern of variation of DO, pH, etc. with respect to the depth of the pond.

It is proposed to study the following chemical and biological parameters at different depths in the pond:

(1) Algae concentration - would determine the amount of algae produced and consequently the oxygen produced.

(2) Dissoved oxygen - would determine the aerobic and anaerobic zones and also the stratification if it exists.

(3) 5-D-BOD & 1-D-BOD - would determine the organic matter removals, 1-D-BOD being required for oxygen mass balance in the pond.

(4) Temperature

(5) Alkalinity - would indicate chemical changes taking place during photosynthesis.

(6) pH - for correlation with alkalinity variation.

(7) Total phosphates - to study their variation with pond processes.

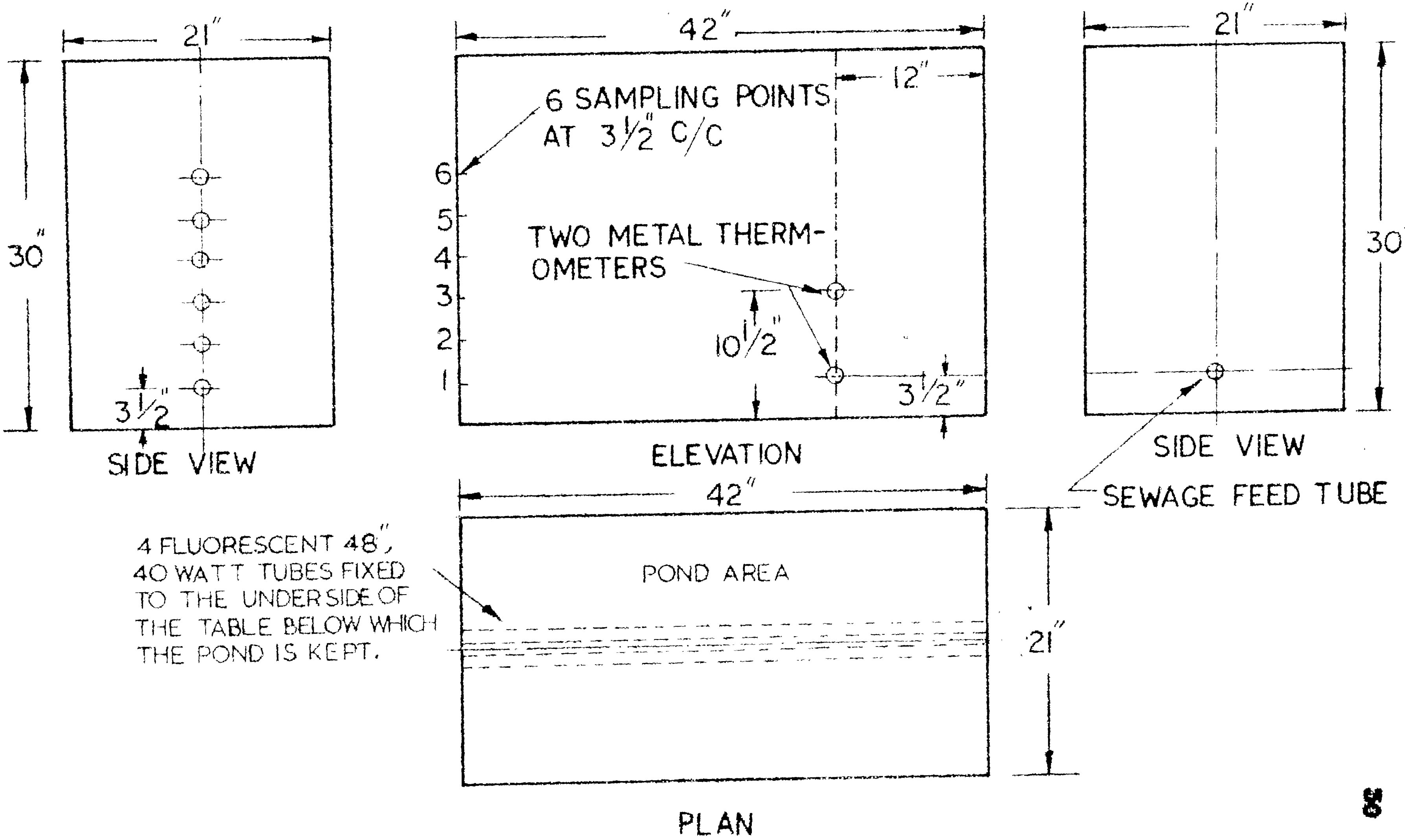
(8) Ammonia-N and Organic-N - to study their variation with respect to stratification and their recovery in the pond in the form of algal cell production.

(9) MPN - to assess how the pond environment affects Coliform survival.

3.4 EXPERIMENTAL SET-UP:

A model of the oxidation pond was designed for the experimental purpose. It consisted of a tank of 18 gauge glazed iron sheets. The size of the tank was 42 inches (107 cms) long, 21 inches (53.5 cms) wide and 30 inches (76.2 cms) deep. The area of the tank was 882 sq inches (5690 sq cms). On one smaller side of the tank a whole was made in the middle of the side, 3.5 ins. (8.9 cms) from the bottom. This hole was used for feeding the tank with the sewage. On the opposite smaller side, six holes were drilled midway between the edges starting from 3.5 ins. from the bottom and 3.5 ins. Centre to centre. The holes were 0.5 inch (1.27 cms) diameter (see Fig. 3.1). The topmost hole 21 ins. from the bottom is for the effluent in runs I and II; and the fourth hole from the bottom, 14 inches from it, is for effluent in runs III and IV. The level of water in the tank was maintained 0.25 ins. (0.6 cms) above the effluent holes to ensure easy withdrawal of effluent samples. The numbering of the holes which are the sampling points for taking samples at various levels is indicated in Fig. 3.1. Two thermometers were inserted in the front broad side at 3.5 ins. and 10.5 ins. from the bottom, as shown in Fig. 3.1, to measure temperatures.

FIG. 3·1
EXPERIMENTAL POND DETAILS



All the holes used for sampling as well as feeding were fitted with rubber corks through which glass tubes were inserted after drilling holes through them. Adequate lengths of rubber tubing were fitted to the outside ends of these glass tubes. This experimental pond was now placed below a laboratory work-table the underside of which four fluorescent tubes were fixed for providing light on the pond.

3.5 PREPARATION OF MODEL OXIDATION POND:

In order to simulate the field conditions properly in the matter of seeding the pond with microorganisms, the bottom of the tank was covered by a layer of soil, 0.5 ins. in thickness, and later the tank was filled upto about 10 ins. ffom the bottom with water brought from an outside pond. As the outside pond was in existence for a long time, there would be a good growth of algae and other microorganisms in it. A microscopic examination of this water sample confirmed that it contained different types of algae, protozoa, etc. The remainder of the pond upto the height of 21 ins. was filled with feed sewage. Initially to obtain a good growth of algae and to get the pond working satisfactorily, no feeding was done for about ten - fifteen days. During this peridd sometimes the nutrients like ammonium sulfate and potassium phosphate were added to the pond. The development and growth of algae

in the pond was reflected in the changing colour of water which became greener and greener. After this period, the regular feeding and effluent withdrawal was started.

3.6 THE LIGHTING ARRANGEMENT:

Four tubes of 40-watt, T-12, 48 in. (Phillips) long giving fluorescent light were fixed to the underside of the laboratory table below which the experimental pond was placed. When the depth of water in the pond was 21 inches, the vertical distance between the water surface and the centre of the tubes was 12 in.; when the pond water depth was 14 in., the same distance was 19 inches.

From the typical fluorescent tube data (34), each tube gives 750 lumens per ft length of the tube. For calculating the illumination in foot-candles at distances of 12 in. and 19 in. the same reference gave horizontal distribution factors of 0.127 and 0.145 at a sideways distance of 1 ft. from the centre of the tubes on the water surface. Here the light intensity is supposed to be least. So the illumination for the two depths are 381 ft-candles for 12 inch distance and 435 ft-candles for 19 inch distance.

About 16.5% of radient energy is converted into light(34) apart from convection and heating losses. From the study of light distribution on the model, it was taken that about 60% of the light would fall on the water surface. The light

energy falling on the pond surface per day in calories per sq. cms. would be $0.6 \times 0.165 \times (4 \times 40) \times 24 \times 3.6 \times 10^3 / 4.187 \times 5690$ or about 60 calories per sq. cm. per day. This would be so when the lights are on for 24 hours a day. From Oswald's chart(13), which gives the probable values of solar radiation falling on the ground as a function of lattitude and month, the value of 60 calories per cm^2 per day corresponds to less than the minimum solar radiation in Kanpur (26.5° N) for the month of December.

3.7 STARTING THE POND:

With lights kept on 24 hours a day, the pond conditions were under a careful watch. Occasionally, as stated previously (in section 3.5), nutrients like ammonium sulphate and potassium phosphates were added at the rate of 15 mg/l and 5 mg/l respectively. These quantities were based on the work of Neal and Hopkins(35). The pond conditions in terms of dissolved oxygen started improving and after about 15 days the pond became dark green. Then the feed of domestic sewage was started gradually till it became 50 lbs. of BOD/acre per day or for domestic sewage of 200 mg/l of 5-D-BOD, the feed was 16 litres/day. The strength of the feed sewage was kept constant at that value.

3.8 PLANNING OF EXPERIMENTAL PROCEDURE:

The experimental procedure was planned to fulfil the

objectives of the study. The plan of work is briefly presented below:

(1) Control Variables: The control variables in the present study were (a) depth of the pond and (b) rate of BOD feed. The values of these variables are already stated in section 3.2. The strength of the feed sewage was kept constant at 200 mg/l of 5-D-BOD by appropriate dilution. For this, first the relationship between 5-D-BOD and COD of the feed was established and the parameter of COD was used to keep the sewage strength constant. With this strength the feed rates for the two BOD loads of 50 and 100 lbs/acre/day came out to be 16 litres/day and 32 litres/day respectively for the given pond.

(2) Depth of the Feed Point: The feed was introduced from the hole made in one of the smaller sides of the tank. The height of the hole was 3.5 inches (8.9 cms) above the bottom. The sewage was fed into the tank every day in the morning at about 10 a.m.

(3) Feed Material: The feed material proposed is the effluent of the domestic waste from the septic tank in the IIT Campus. The same manhole was used all the time. The characteristics of this sewage were, more or less, constant and predictable, and when taken from the same manhole every day at about the same time, its strength was also more or less constant.

(4) Light Intensity: The light intensity was kept constant at the rate of 60 cals/sq cm of pond area per day when the lights were on all the time.

(5) Sampling: The samples were withdrawn from the sampling points of the pond model every day at about 12 noon. The samples were initially tested for DO and pH to determine the steady state. About 100 ml were withdrawn from every sampling point for these tests. DO determinations were done in smaller bottles of 50 ml capacity.

(6) Tests: When the steady state was reached, all the experimental parameters mentioned in section 3.3 were determined at all the sampling points. Except algae concentration determination, all the parameters were determined according to the procedure given in 'Standard Methods' (36). Algae concentration was determined photometrically as described in section 3.8.2. There are in all four runs of the experiments, two corresponding to 21 in. depth of pond and two BOD loads of 50 and 100 lbs./acre/day and the other two corresponding to 14 in. depth of pond and the same two BOD loads.

However, before the first steady state was reached, the following experimental determinations were made which were of the nature of preparation of standard curves for determining the chemical parameters later on.

3.8.1 Relationship between 5-D-BOD and COD of Feed Sewage:

This was necessary to regulate the feed to a constant BOD of 200 mg/l. The COD test is preferred to 5-D-BOD test as it is quite quick. Both the tests were performed on the feed sewage samples on number of days and data obtained for 5-D-BOD were plotted against the corresponding COD values. These tests were conducted according to 'Standard Methods'(36) and the results are tabulated in Table 1 and shown in Fig. 1 in Appendix.

3.8.2 Construction of a Photometric Standard Curve for the Estimation of Algae:

It was seen that the algae-laden water looks quite green. It was proposed to measure the concentration of algae at various depths by measuring the intensity of green colour photometrically. This can be found by measuring the absorbance at a predetermined wavelength of the algae water. The concentration of algae in pond water can be found out, in mg/l by centrifuging the algae and finding its dry weight after drying it for two hours at 105° C. As there would be some absorbance of light by the sewage turbidity, it is proposed to use that frequency for determination of absorbance at which the difference between the absorbance of algae water and sewage is maximum.

The appropriate data for determination of optimum wavelength is given in Table 4 and plotted in Fig. 4 in

Appendix. And the data for the preparation of standard curve for determination of algae concentration is given in Table 5 and plotted in Fig. 5 in Appendix.

3.8.3 <u>Determination of Standard Curves for Total Phosphates and Ammonia Nitrogen</u>:

These curves are necessary for the determination of concentrations of total phosphates and ammonia nitrogen of the samples photometrically. The curves were constructed according to the procedure given in 'Standard Methods' (36). The data and the standard curves are given in Appendix in Tables 2 and 3 and Figs. 2 and 3 respectively.

3.8.4 <u>Determination of BOD Rate Constants for Samples at Depths</u>:

These values are needed for the mass balance of oxygen per day in the pond.

The BOD values on various days starting from the first are determined according to a procedure similar to 5-D-BOD test. The temperature for all the tests was 25° C. The data obtained was treated according to Fugimoto method(37). The samples for the tests were withdrawn at various levels at the same time. The results and Figs. are presented in Table 6 and Figs. 5 to 10 respectively in the Appendix.

CHAPTER - IV

OBSERVATIONS AND CALCULATIONS

4.1 CHARACTERIZATION OF FEED SEWAGE:

The feed for the experimental oxidation pond consisted of the effluent from the septic tank in IIT Campus. Characteristic chemical, physical and biological parameters for the feed sewage have the values given in Table 4.1. The procedure followed for these tests was that given in 'Standard Methods'(36).

4.2 DETERMINATION OF STEADY STATE PARAMETERS UNDER DIFFERENT CONDITIONS OF DEPTHS AND FEEDS:

Determination of parameters for the steady state reached under various depths of pond and rates of feed was done following the procedure given in 'Standard Methods'(36). The observations obtained for the four runs are tabulated in Tables 4.2 to 4.5. As decided from the second run onwards, a set of samples from various depths was centrifuged to remove algae from it and additional determinations of 5-D-BOD, 1-D-BOD, ammonia-N and organic-N were done on these. The values obtained are indicated by a star on them in the Tables 4.2 to 4.5.

4.3 CALCULATIONS:

(1) Mass Balance for Biochemical Oxygen Demand:

The mass balance is done by calculating ultimate BOD

of the sewage coming in and going out of the pond per day as well as oxygen produced by algae per day. A typical calculation for run II is presented below:

Influent BOD = 100 lbs/acre/day = 32 litres of 200 mg/l 5-D-BOD feed sewage for the area of the pond.

So, BOD coming in the pond per day = $32 \times 200/(1-e^{-kt})$

= 7360 mg/day

where k is BOD rate constant and t the time in days. (The value of k for the effluent is 0.4 per day as determined by BOD tests. See Table 6 and Fig. 6 in Appendix).

And BOD going out of the pond in effluent (without algae) = $32 \times 32/(1-e^{-0.4 \times 5})$ = 1180 mg/day.

So BOD satisfied in the pond per day = 7360 - 1180

= 6180 mg/day.

Algae concentration (dry wt) in the effluent = 105 mg/l

Oxygen produced by algae = $32 \times 105 \times \underline{1.65}$ = 5550 mg/day.

So, balance of BOD satisfied anaerobically = 6180 - 5550

= 630 mg/day.

(The data for the run II are given in Table 4.3).

(In the run I, the effluent was being released from the sampling point 4 instead of 6 - that is, 7 inches below the pond level. As the algae which had maximum concentration in the top layer went out only partially with the effluent, the value of algae produced per day, as

measured from the sample from point 6, is quite high. From the literature it can be seen that a value for algae concentration for the BOD loading of the order of 50 lbs/acre/day and light intensity of the order of 130 cals/sq cm/day would be of the order of 100 mg/l (14). Hence this value has been used in the calculation for run I. Also the theoretical BOD of the algae works out to be 0.68 mg/mg of algae. Similarly, for the production of oxygen from algae a factor of 1.65 mg of oxygen per mg of algae is taken from the literature(13,14). These values would then indicate the effluent BOD to be 27 mg/l, and the remaining 68 mg/l BOD would be that which is exerted by dead algae. The amount of algae needed for this would be about 100 mg/l).

Similar mass balances are made for other runs and the results are presented in Table 4.6.

(2) Mass Balances for Ammonia-N and Organic-N:

In calculating the mass for nitrogen the sum of ammonia-N and organic-N is termed total nitrogen. From the literature survey it is seen that most form of algae in mass contain about 8% of nitrogen(13). The mass balance for nitrogen is calculated similar to that of BOD and the results are presented in Table 4.7.

4.4 OBSERVATIONS:

All the observations are recorded in appropriate tabular form, from Tables 4.1 to 4.7 and the graphs are presented in Figs. 4.1 to 4.4.

TABLE 4.1

CHARACTERISTICS OF THE FEED SEWAGE

Parameter	Range	Average Value
Temperature	20° - 28° C	25° C
pH	8.2 - 8.6	8.3
COD	290 - 350 mg/l	300 mg/l
Total solids, fixed	490 - 600 mg/l	550 mg/l
" " volatile	250 - 400 mg/l	300 mg/l
Dissol. " , fixed	280 - 500 mg/l	450 mg/l
" " , volatile	140 - 290 mg/l	200 mg/l
Chlorides	90 - 160 mg/l	140 mg/l
Ammonia-N	9 - 15 mg/l	12 mg/l
Organic-N	16 - 28 mg/l	20 mg/l
Total phosphates	6 - 10 mg/l	8 mg/l
Alkalinity	460 - 600 mg/l	500 mg/l
MPN	1 to 15×10^7/100 ml	9×10^7/100 ml

TABLE 4.2

STEADY STATE PARAMETERS FOR RUN 1

Pond depth = 21 ins. BOD load = 50 lbs/acre/day

Detention time = 20 days Light intensity = 60 cals/cm^2/day

	Sampling Points					
Parameter	6	5	4	3	2	1
Depth, cms, below pond level	Nil (Efflu.)	8.9	17.8	26.7	35.6	44.5
Temp., °C	27.5	-	-	26.5	-	26
pH	8.35	8.20	8.15	8.0	7.90	7.65
DO, mg/l	3.20	2.80	2.05	1.35	0.40	0.00
5-D-BOD, mg/l	95	87	85	81	83	84
1-D-BOD, mg/l	36	36	32	31	36	37
Algae conc., mg/l	250	200	25	5	0	0
NH_3-N, mg/l	3.6	3.5	3.5	3.4	4.5	4.8
Org-N, mg/l	15	13	10	10	11	11
Total Alkal., mg/l as $CaCO_3$	270	290	340	320	310	315
Total Phos. mg/l	2.8	2.9	2.7	3.1	3.2	3.1
MPN,	0	0	0	0	0	0

TABLE 4.3

STEADY STATE PARAMETERS FOR RUN II

Pond depth = 21 ins. BOD load = 100 lbs/acre/day

Det. time = 10 days Light inten. = 60 cal/cm^2/day

Parameter	Sampling Points 6	5	4	3	2	1
Depth, cms, below pond level	nil (efflu.)	8.9	17.8	26.7	35.6	44.5
Temp., °C	28	-	-	26.5	-	26
DO, mg/l	2.04	1.20	0.32	0.00	0.00	0.00
5-D-BOD,	102	93	75	85	89	91
mg/l	32*	35*	45*	82*	85*	90*
1-D-BOD,	38	35	30	33	34	35
mg/l	13*	14*	17*	31*	33*	35*
Ammonia-N,	5.1	4.3	4.0	4.3	3.8	4.1
mg/l	4.1*	4.2*	3.9*	4.2*	3.8*	3.9*
Organic-N,	16	15	10	9	10	10
mg/l	9*	8*	7*	8*	9*	8*
Total Phos., mg/l	2.3	1.9	2.1	2.3	2.3	2.4
Algae conc., mg/l	105	85	25	10	0	0
Alkalinity, mg/l of $CaCO_3$	328	323	360	390	390	380
MPN, /100 ml	0	0	0	0	0	0

*Values in samples that were centrifuged to remove algae.

TABLE 4.4

STEADY STATE PARAMETERS FOR RUN III

Pone depth = 14 ins. BOD load = 50 lbs/acre/day

Det. time = 12.6 days Light inten. = 160 cals/cm^2/day

Parameters	Sampling Points 4	3	2	1
Depth, cms, below pond level	nil (efflu.)	8.9	17.8	26.7
Temp., °C	28.5	27.0	-	26.5
pH	8.4	8.1	8.0	7.8
DO, mg/l	3.0	2.18	1.45	0.6
5-D-BOD,	105	93	81	88
mg/l	35*	37*	38*	41*
1-D-BOD,	35	33	33	34
mg/l	8*	14*	21*	24*
Algae conc., mg/l	110	80	40	15
Ammonia-N,	4.1	3.8	3.2	3.5
mg/l	4.0*	3.6*	3.1*	3.5*
Organic-N,	17	15	12	10
mg/l	9*	9*	8*	10*
Alkalinity, mg/l as $CaCO_3$	322	319	330	323
Total Phos., mg/l	2.1	1.9	2.3	2.4
MPN,/100 ml	0	0	0	0

*Values in samples that were centrifuged to remove algae.

TABLE 4.5

STEADY STATE PARAMETERS FOR RUN IV

Pond depth = 14 ins. BOD load = 100 lbs/acre/day

Det. time = 6.3 days Light inten. = 160 cals/cm^2/day

Parameters	Sampling Points 4	3	2	1
Depth, cms, below the pond level	0 (efflu.)	8.9	17.8	26.7
Temp. °C	28.5	27.5	-	26.5
pH	8.75	8.15	7.90	7.70
DO, mg/l	1.80	0.94	0.00	0.00
5-D-BOD,	120	90	59	60
mg/l	39*	37*	40*	41*
1-D-BOD,	46	36	23	24
mg/l	15*	14*	15*	16*
Algae conc., mg/l	114	85	20	0
Ammonia-N,	4.1	3.9	3.4	3.5
mg/l	4.0*	3.8*	3.3*	3.5*
Organic-N,	16	14	10	10
mg/l	7.5*	8.0*	7.5*	7.6*
Total Phos., mg/l	2.2	2.1	1.9	2.3
Total Alkalinity, mg/l as $CaCO_3$	339	332	340	340
MPN / 100 ml	0	0	0	0

*Values in samples that were centrifuged to remove algae.

TABLE 4.6

MASS BALANCE FOR BOD AND OXYGEN PRODUCED

Run	BOD infl. mg/day	BOD effl. mg/day	O_2 produced by algae mg/day	Balance of oxy. demand mg/day	Remarks
Run I: BOD load 50 lbs/acre/day; Det. time 20 days; Pond depth 21 ins.	3680	496	2640	544	This balance, 17.1% of BOD satis. is satisfied anaerobically in bottom layer. BOD removal 86.5%.
Run II: BOD load 100 lbs/acre/day; Det. time 10 days; Pond depth 21 ins.	7360	1180	5550	630	This balance of 10.5% of BOD satis. is satis. anaerobically in 3 bottom layers. BOD removal 84%
Run III: BOD load 50 lbs/acre/day; Det. time 12.6 days; Pond depth 14 ins.	3680	645	2900	135	This balance 0.02% of the BOD satis. is satis. in a small layer at the bottom which may be anaerobic. BOD removal 82.5%.
Run IV: BOD load 100 lbs/acre/day; Det. time 6.3 days; Pond depth 14 ins.	7360	1180	5200	980	This balance, 14.4%of BOD satis. is satis. in bottom 2 layers anaerobically. BOD removal 84%.

TABLE 4.7

MASS BALANCE FOR NITROGEN

Run	N-coming in mg/day	N-going out mg/d.	Balance of N, mg/day	Total Prod. of algae mg/day	N-recovered as algae mg/day	% N recovery	% N lost to the system.
I: BOD load 50 lbs/acre/day; Det. time 20 days; Dep. 21 ins.	512	298	214	1600	128	25	16.7
II: BOD load 100/ lbs/acre/day; Det. time 10 days; Dep. 21 ins.	1024	418	606	3360	269	26.3	32.8
III: BOD load 50 lb /acre/day; Det. time 12.6 days; Dep. 14 ins.	512	208	304	1760	141	27.5	31.9
IV: BOD load 100 lbs/acre/day; Det. time 6.3 days; Dep. 14 ins.	1024	369	655	3650	267	26	37.8

FIG. 4·1

DISSOLVED OXYGEN Vs DEPTH

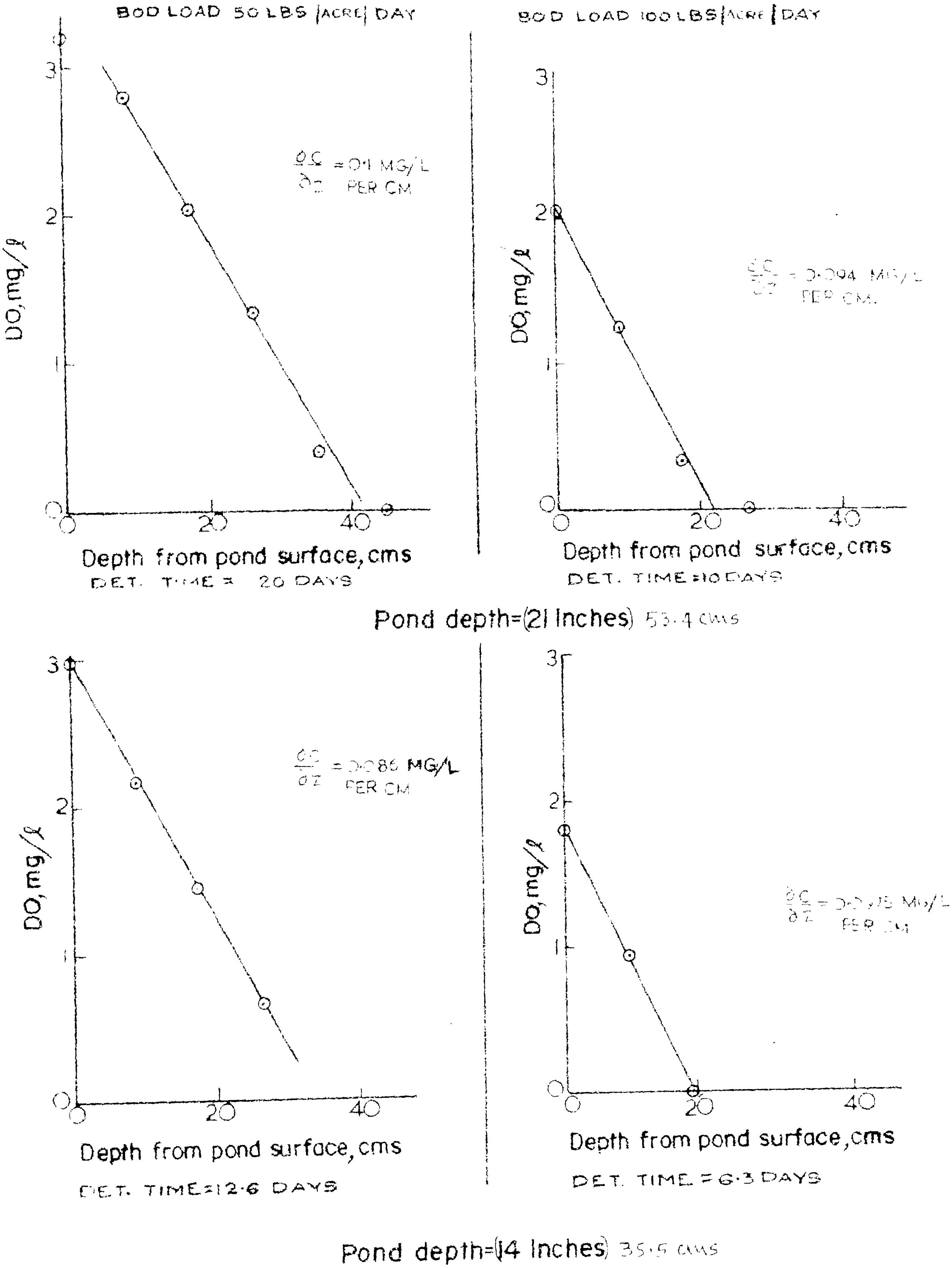
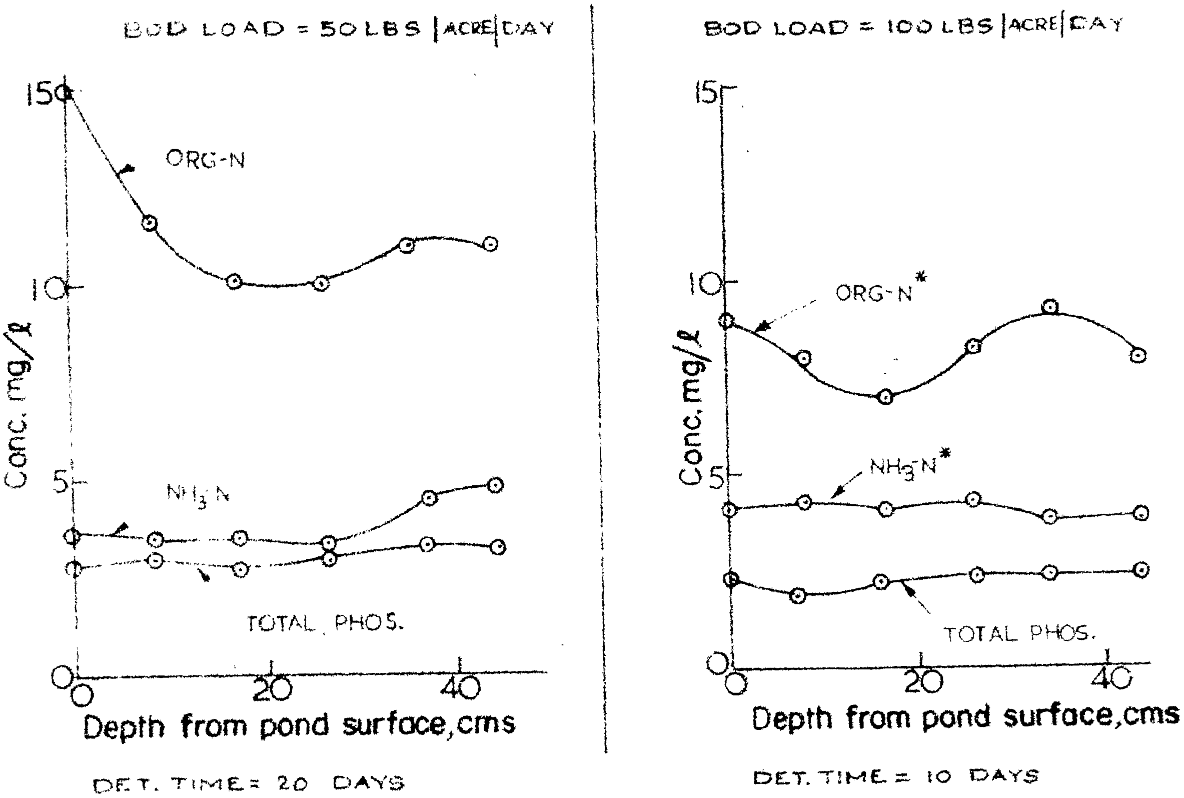
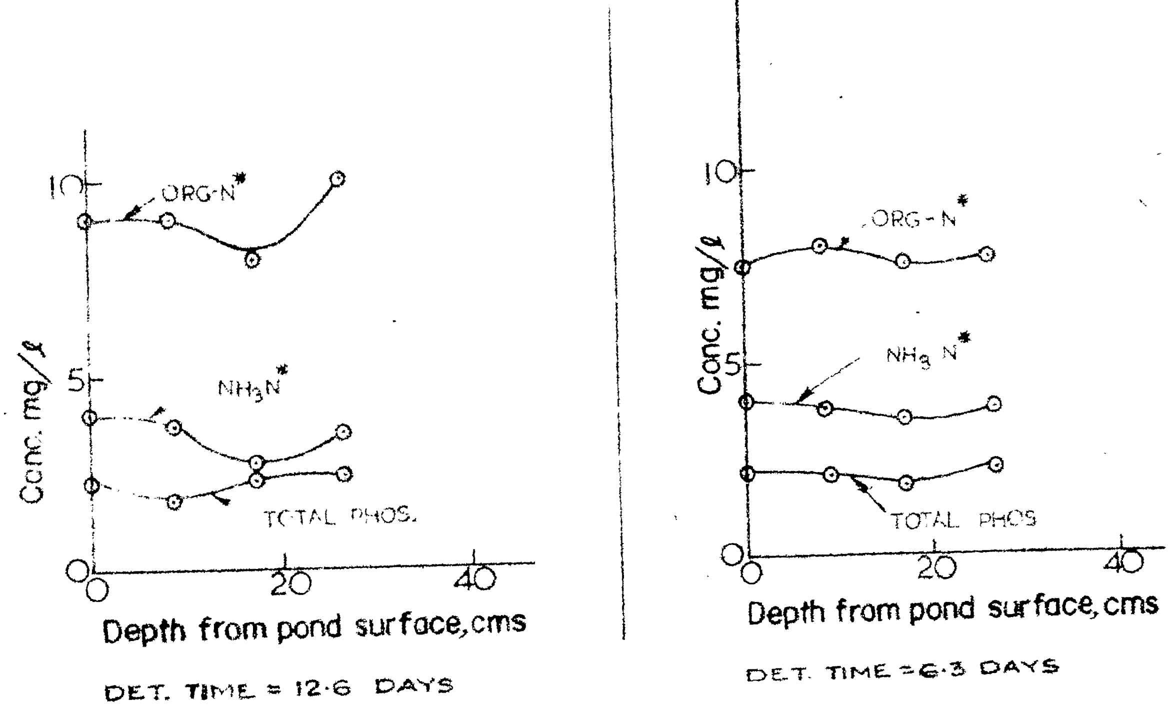


FIG. 4-2

ORG-N, NH_3-N, TOTAL PHOSPHATES Vs DEPTH



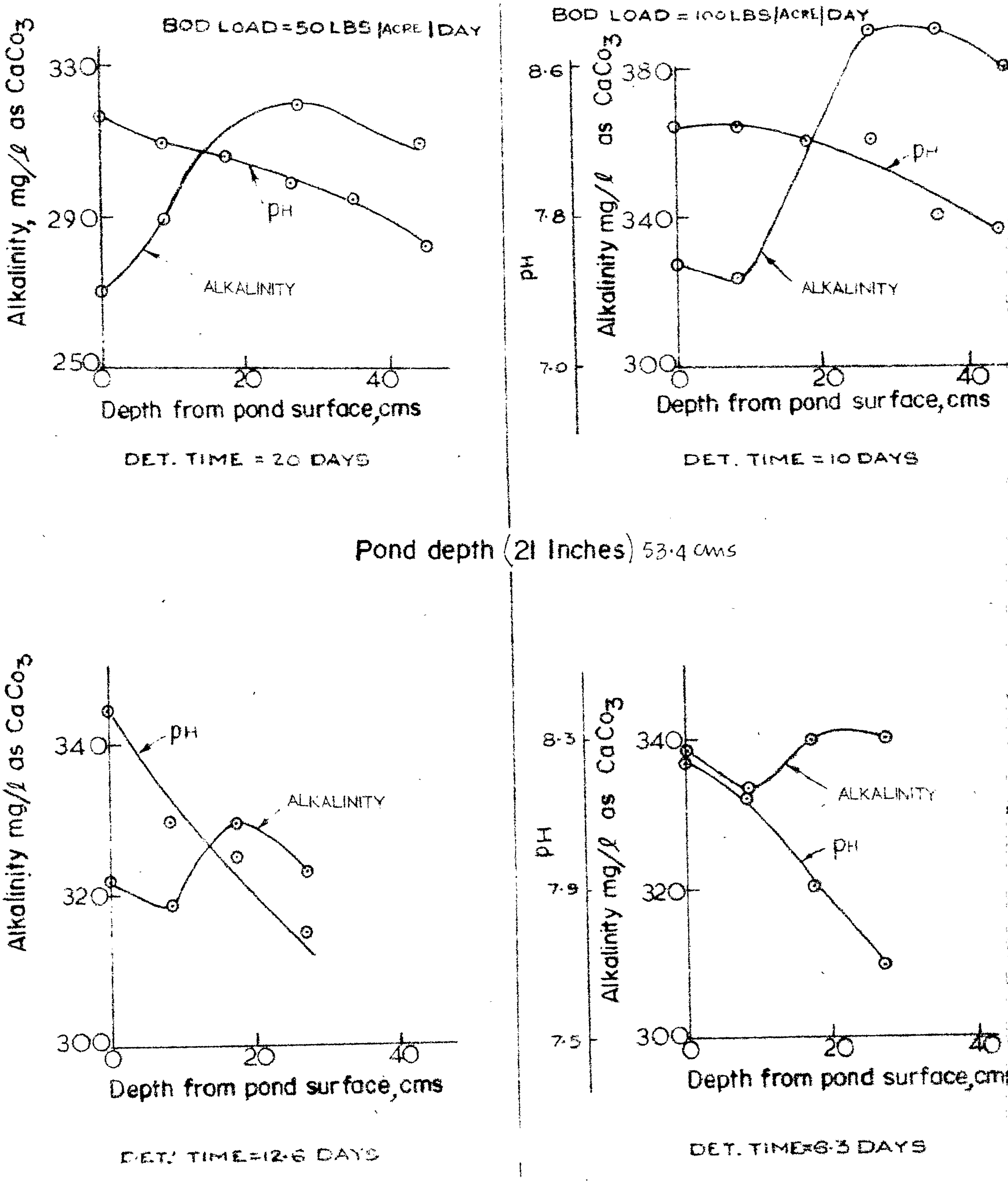
Pond depth = (21 Inches) 53.4 cms



Pond depth (14 inches) 35.5 cms

FIG. 4·3

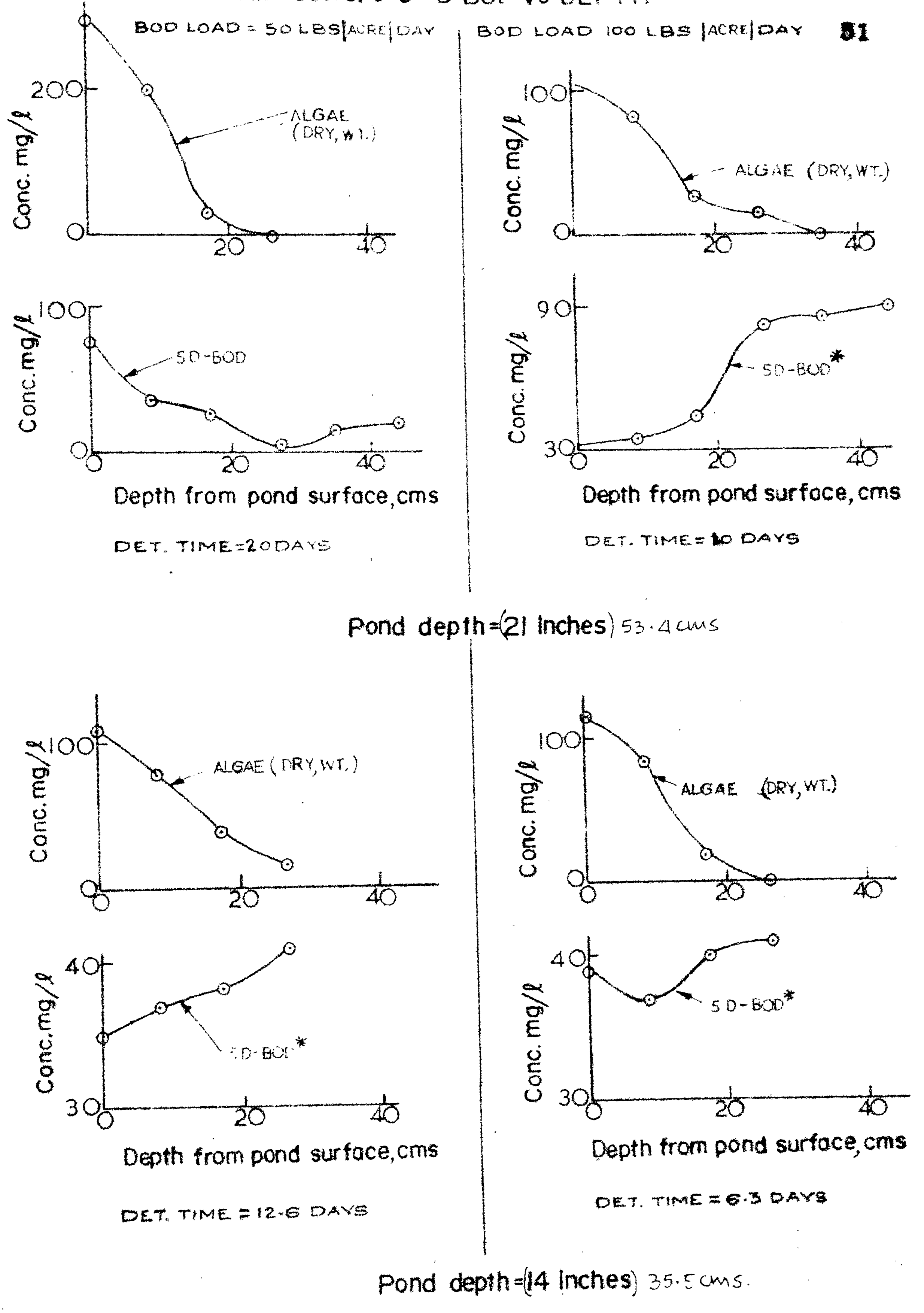
ALKALINITY & PH Vs DEPTH



Pond depth (14 Inches) 35·5 cms

FIG. 4·4

ALGAE CONC. & 5-D BOD Vs DEPTH



CHAPTER - V

DISCUSSION AND CONCLUSIONS

5.1 STRATIFICATION IN OXIDATION PONDS:

The experimental results in the previous chapter indicate that stratification exists even in small-depth oxidation ponds in conditions which would have been expected to be condusive to a completely aerobic system. This is indicated from the study of alkalinity, organic-N and the 5-D-BOD values as discussed below. This stratification exists, however, under the given experimental conditions which include lighting for all the 24 hours.

5.1.1 Alkalinity:

The alkalinity in the pond depends upon the activity of the photosynthetic algae and the alkalinity of the incoming sewage. Algae utilizes CO_2 as the source of carbon which is supplied by bacteria while oxidizing organic matter aerobically. HCO_3^- ions also supply CO_2 to the algae. It can be seen (Fig. 4.3) that in the first 10 cms depth of pond, alkalinity decreases from 328 to 324 mg/l in run II; from 324 to 318 mg/l in run III and from 337 to 333 mg/l in run IV. This decrease is of the order of 4 to 6 mg/l which in the present experimental pond is almost negligible. So, in the first 10 cm depth the magnitude of alkalinity is low compared to the higher values at the deeper levels, and these low values remain

more or less constant for the layer of 10 cms depth. The values of alkalinity as observed in run I may not be reliable. As the effluent in run I was released from the sampling point 4, which is 7 inches below the pond level, it would not draw out enough algae in the effluent as most of them would be in the upper surface layers. Naturally, the value of algae concentration in the sample drawn from sampling point 6 (pond surface) would be high. The actual per day production of algae reflected in the algae concentration in the effluent would be much less. This difference might have affected the alkalinity values also.

The other zone of higher alkalinity is formed at lower depths. Between 25 and 35 cms depth in run II, alkalinity is almost constant at its maximum value of 390 mg/l. In run III the layer around 17 to 21 cms depth has the alkalinity value of 330 mg/l and in run IV the layer between 20 and 25 cms depth has alkalinity of 340 mg/l (Fig. 4.5). These values show that there is a layer of high alkalinity at about mid-depth for the pond having 53.4 cms (21 inches) depth and a little below mid-depth (about 0.57 depth) for the pond having 35.5 cms (14 inch) depth.

In bottom layers, the alkalinity values are lower than the maximum ones reached earlier at about mid-depths.

This indicates that the oxidation pond has three layers, two of low alkalinity at top and bottom and one of high alkalinity approximately in the middle, the alkalinity in the intervening layers either increasing or decreasing gradually.

5.1.2 Organic-Nitrogen:

Organic-N values of samples centrifuged to separate algae is another parameter that points towards the stratification in the pond. Although in the first run, the organic-N decreases rather fast from 15 to 10 mg/l in the first 18 cms depth, this cannot be relied upon because of the effluent height difference as explained in section 5.1.1. In the second run in the first 10 cms depth, the decrease is only from 9 to 8 mg/l; in the third run, the organic-N is constant at 9 mg/l for the first 10 cms depth and in the run IV, there is a very small increase from 7.5 to 8 mg/l in the same depth (Fig. 4.2). These values indicate that the organic-N remains more or less constant in the first 10 cms depth.

The minimum values of organic-N are reached at lower depths; in run I, around 18 to 28 cms depth; in run II, around 20 cms depth; in run III, around 18 cms, and in run IV, around 19 cms depth. The concentration thereafter again rises to the maximum to 9 mg/l at 35 cms depth in run II, and to 10 mg/l at 27 cms depth in run III. In the run I, the

value is 11 mg/l around 40 cms depth and in run IV, the maximum value in the bottom layers is only slightly higher than the minimum value. From all this it can be said that the layer of higher organic-N at the top is followed by a lower organic-N layer around 20 cms depth. This again is followed by a higher organic-N layer at the bottom. The depths of these layers seem to depend more on the total depth of the pond than on the rates of feed.

5.1.3 <u>5-D-BOD Values</u>:

In the first 10 cms layer, the BOD values of the samples that are centrifuged to remove algae are lower (about 36 mg/l for runs II, III and IV, the first run showing haphazard variation due, perhaps, to the reason mentioned in section 5.1.1) whereas the values are maximum in the bottom 10 cms layer (85 for run II and about 40 for runs III and IV, Fig. 4.4). In between, the values rise gradually from the top to the bottom. So, there is a lower BOD layer near the top and one of higher BOD at the bottom with the intermediate layers having BOD values that have almost a gradual transition.

5.2 <u>THE STRAIGHT LINE VARIATION OF DISSOLVED OXYGEN</u>:

In the present study, the straight line variation of DO (Fig. 4.1) w shows that there is infinite stratification with respect to DO in the pond, and this does not go against the hypothesis advanced in this work. It is important to

remember that for facultative pond the depths of 14 and 21 inches are not high. The usual ponds would have depths much more than these. Another fact can also be noted that the algae production along the depth is varying uniformly. Fig. 4.4 shows almost a straight line variation of algae for runs II, III and IV. It means that neither the depth nor the light intensity was limiting for algae growth and the light penetrated uniformly the portion of the pond that was aerobic. As the algae production is uniform the oxygen produced would also be uniform. Also the 5-D-BOD value, barring the 10 cm zone at the top and bottom, also varied uniformly. So the oxygen consumption along the depth could be taken as uniform. Therefore, the remaining DO at various levels also would be uniform. This, perhaps, would explain the straight line variation of DO with depth. However, when the depths are large, the light intensity at lower depths would be an exponential function as given by Beer-Lamberts law. Under such a condition the DO variation is likely to be an exponential curve. More work will have to be done with greater depths of pond to clarify this point.

5.3 PRODUCTION OF ALGAE WITH DIFFERENT DETENTION TIMES:

The production of algae with two depths and two rates of feed gives an interesting variation. If the

production per day is considered as given in Table 4.7. It can be seen that as detention time is halved by doubling the feed volume, the algae production is also almost doubled. The depth did not affect the algae production, because as we have seen the light intensity is not a limiting factor. This clearly shows that there is greater growth of algae with decrease in detention time and that this relationship may be linear as is indicated in the present study. However, more experiments will have to be performed to decide this issue.

It is known from work done on continuous cultures of such microorganisms as bacteria and fungi (but not algae)(39) that in cultures, until some component of the substrate becomes limiting, the steady state growth of cell mass follows a linear growth law. Initially, when the dilution rate is increased, (i.e., the detention time is decreased) the cell mass growth increases linearly upto a certain dilution rate and thereafter with further increase in dilution rate, it is reduced precipitously to what is called 'wash-out' when the dilution rate is such as to wash all the cell mass out of the culture. This conclusion is also supported by Herbert et al(40) with their theoretical and experimental study of continuous bacterial cultures.

In the present study, although the oxidation pond system is not a continuous growth culture, the algae growth seems to follow a similar trend with respect to detention

time. Perhaps, some constituent in sewage feed makes the substrate growth-limiting so as to make the algal culture follow the same or similar law mentioned in the previous paragraph. This finding is of great importance from the design standpoint because the ponds can be made to work more efficiently for algal yields and BOD removals per day by decreasing the hydrolic detention time by some such method as recirculation of pond effluent after algae-harvesting or mixing the feed waste water with canal or stream water.

5.4 THE DISCREPANCY BETWEEN ALKALINITY AND pH VARIATION:

The study of Fig. 4.3 shows that the pH drops almost uniformly with depth. In no case pH value increased for the lower layer compared to the value of pH for the upper layer. But the alkalinity change is not at all gradual. In run II, alkalinity drops from 330 mg/l at the top level to 324 mg/l at 10 cms depth; then it increases to 390 mg/l at about 33 cms depth. Similarly, in run III, from a drop of 3 mg/l in the first 10 cms depth, it rises to 330 mg/l at 20 cms depth. It can be seen from these values that there is no rise in pH value corresponding to higher values of alkalinity. According to presently accepted theory, the algae utilizes CO_2 from HCO_3^- ion according to the reaction $HCO_3^- \quad CO_2 + OH^-$ and the pH should rise because

the CO_2 is utilized faster by algae than it is replaced by the bacterial oxidation of organic matter. Also any decrease in bicarbonate alkalinity is compensated by equivalent rise in OH^- ions. There should be, therefore, no decrease in alkalinity as observed. It is worthwhile to note in this connection that Myers and Crammer(38) have shown that when ammonia is employed as a nitrogen source for algae, the consumption of 1M of NH_3 is accompanied by the production of 1M of H^+ ion. Because most of the nitrogen in oxidation pond is present as NH_3 and/or organic-N which is converted to NH_3 by bacteria, it is likely that much of the decrease in alkalinity in the upper layers of pond may be ascribed to the nitrogen metabolism of algae. However, as the present observation is contrary to the accepted theory, more work is indicated to test the hypothesis of production of H^+ ion in the pond by algae.

5.5 VARIATION OF TOTAL NITROGEN AND NITROGEN RECOVERY:

The small amount of ammonia-N in the effluent (from 3 to 4 mg/1, Fig. 4.2) shows that algae utilize most of the nitrogen in the form of ammonia.

Table 4.7 shows that the recovery of total nitrogen is only of the order of 86% whereas quite an appreciable percentage is lost to the system. In run I, where only the bottom 3.5 inches layer is anaerobic, the nitrogen loss is 16.7%; in run II, the bottom 10.5 inches of pond is

anaerobic and the nitrogen loss is 32%; in run IV, the bottom 7 inch layer is anaerobic and the nitrogen loss is 37.8%. The feed rates for runs I and III and for II and IV are 50 lbs and 100 lbs per acre per day respectively. These values indicate that the nitrogen loss from the system perhaps depends upon feed rate of BOD load. The loss itself can, perhaps, be explained on the basis of denitrification taking place in the anaerobic zones of the pond according to the scheme

$$NO_3^- \longrightarrow NO_2^- \longrightarrow N_2 \text{ (gas)}$$

and the gas finally escaping into the atmosphere. Or, it can also be attributed to the nitrogen loss due to settlement of organic matter and the dead algae to the bottom of the pond. The processes of sedimentation and bioflocculation are already explained in section 2.12.3. The nitrogen then would be contained in the benthic deposits. No test for nitrogen was carried out on the sludge deposited at the bottom of the oxidation pond. The nitrogen loss of 31.9% in run III is inexplicably high, as here, perhaps, only the bottom 1 to 2 inch layer will be anaerobic. Although some gas bubbles were observed on the pond surface during the various runs, no attempt was made to identify the gases. One of the gases evolved could have been nitrogen especially when the pH values from 7.8 to 8.3 predominated in the middle and upper layers of the pond. This range of pH is favourable for denitrification to occur. So it can be said

that the nitrogen loss could be because of any one of the two possibilities, denitrification or settlement of organic matter and dead algae, as discussed above. More work on this point is indicated.

Another important point which can be seen in nitrogen balance is that the amount of nitrogen recovered in algae mass is increasing almost to double its value when the BOD load is doubled halving the detention time. This is, of course, due to the fact that the algae production itself is almost doubled. This increase of algal yield with decrease of detention time is already discussed in section 5.5. These observations show that the light intensity is not a limiting factor and that the algae growth can be encouraged (within limits) by decreasing the detention times. This point assumes importance in algae-harvesting for its protein value when the algae can be used as a chicken feed, etc.

5.6 TOTAL PHOSPHATE VARIATION:

It is seen (Fig. 4.2) that when the detention time for run I of 20 days was reduced to 10 days in run II by doubling the feed rate, there was reduction in phosphates at all levels; the same observation, however, is not found for runs III and IV. So, no definite conclusion can be drawn although generally phosphates tend to increase with detention time(25).

perhaps are not comparable for the reason stated in section 5.1.1.

5.8 REDUCTION OF COLIFORMS IN OXIDATION PONDS:

It is clear from the results that in no run was there any value of MPN for the pond waters at any depth. In the present study the smallest detention time is of 6.3 days. Normally it can be expected that the detention time would affect values of MPN.

Actually even now the exact reasons for the removal of the Coliform are not completely known. It was suggested that the algae in oxidation pond may be excreting some substance toxic to Coliform, but in the light of later findings this had to be rejected. It is also known that reduction of Coliform in different seasons is, more or less, the same despite variation in algae content.

Another theory is that with higher detention times the Coliforms are subjected to storage during which there is a lot of settling going on. This coupled with extreme competition for food with other bacteria also cause the redμction of Coliforms. There is also a large difference of pH in the pond from top to bottom.

Perhaps, a large population of protozoa which develop in the pond also reduce the Coliforms by feeding on them. So, on all accounts the environment of oxidation

pond is extremely hostile to the Coliforms. It should be found, however, how their variation is when the detention time is as small as a day or two.

5.9 CONCLUSIONS:

From the present study, the following conclusions can be arrived at. These conclusions are valid for the conditions under which the experimental investigations were conducted.

5.9.1 About Stratification in Oxidation Ponds:

(1) Based on the study of variations of alkalinity, organic-N and 5-D-BOD values, it can be said that stratification exists in the oxidation pond under study. This conclusion is drawn from the following considerations:

(a) In the case of alkalinity, the magnitude is small which either remains more or less constant or decreases in the first 10 cms depth of the pond; then it rises up reaching its maximum by about 20-25 cms depth. Thereafter it has a tendency to decrease. Such a variation shows three strata in the pond: one upto 10 cms depth of lower alkalinity; second between 20 to 30 cms depth where the alkalinity

reaches its maximum value; and third near the bottom of lower alkalinity (Fig. 4.3).

(b) The variation in organic-N also supports the hypothesis of stratification. In this case there is an upper layer which has the highest magnitude of organic-N. When this magnitude drops down, more or less uniformly, to give a second layer of lowest magnitude of organic-N around 20 - 25 cms depth, when the pond depth is 53.4 cms, and around 16 - 20 cms when the pond depth is 35.5 cms. In the lower regions near the bottom the organic nitrogen concentration is again high (Fig. 4.2).

(c) The 5-D-BOD values approximately show a similar stratification (Fig. 4.4). In run II and III, the effluent BOD and that in the top layer have low BOD values. The BOD values are high in the bottom 10 cms depth. In between there is a gradual transition.

(2) Although the DO variation shows that it is a linear one (Fig. 4.1), such a linear variation does not go against the hypothesis of stratification in the oxidation pond. In fact it shows infinite stratification.

This linear variation of DO shows that neither the substrate nor the light intensity was a limiting factor in the present study.

(3) From the BOD balance in Table 4.6 and nitrogen balance in Table 4.7, it is seen that the production of algae per day in the pond increases when the detention time becomes smaller. This may have a certain limit but it was not reached within the four different detention times used.

5.9.2 <u>Other Conclusions:</u>

(1) The variation of alkalinity does not seem to be in accordance with the presently accepted theory. The low alkalinity in top layers of the pond could be due to production of H^+ ions by the algae.

(2) It is seen that in all cases the nitrogen recovery is of the order of 25 to 27%. It is almost constant because the algae concentration increases in the same proportion in which the feed rate increases (or detention time decreases). The percentage of nitrogen lost in the system seems to increase with the feed rate and with decrease in the depth of the pond.

(3) The MPN values are all zero for the four detention

times under consideration which were all greater than six days.

(4) The phosphates and ammonia-N variation does not warrant any significant conclusion.

APPENDIX

(1) RELATIONSHIP BETWEEN 5-D-BOD AND COD OF THE FEED SEWAGE:

Table 1

5-D-BOD and Corresponding COD Values

5-D-BOD mg/l	100	92.5	81.2	135	82.2	75.5	71.3	135	170	105
COD mg/l	156	135	133	220	119	120	100	190	240	170

The data are plotted in Fig. 1 (Appendix).

(2) DETERMINATION OF STANDARD CURVE FOR TOTAL PHOSPHATE & NH_3-N:

Table 2

Total phosphates and corresponding absorbance at 690 m on 'Spectronic-20'. Light path 1 cm.

Total phosphates, mg/l	0.25	0.60	0.75	1.0	1.3	1.85	2.6	3.65	5.0
Absorbance	0.04	0.099	0.105	0.224	0.30	0.40	0.51	0.70	1.0

The data are plotted in Fig. 2 (Appendix).

Table 3

Ammonia-N and Corresponding Absorbance at 430 m on 'Spectronic-20'. Light path 1 cm.

Ammonia-N mg/l	0.5	1.0	1.5	2.0	2.5
Absorbance	0.08	0.22	0.29	0.37	0.51

The data are plotted in Fig. 3 (Appendix).

(3) DETERMINATION OF STANDARD CURVE FOR ALGAE CONCENTRATION:

Determination of Optimum Wavelength

Table 4

Wavelength and the Corresponding Absorbance

Wavelength m	360	380	400	420	440	450	460	480
Absorbance Sewage	0.375	0.340	0.310	0.290	0.270	0.260	0.255	0.240
Pond-water	0.520	0.560	0.600	0.680	0.700	0.640	0.560	0.440

The data are plotted in Fig. 4 (Appendix)

Determination of Standard Curve

Table 5

Algae Concentration and Corresponding Absorbance

at 440 m on 'Spectronic-20'. Light path 1 cm.

Algae Conc. mg/l	300	150	75	37.5	18.7
Absorbance	0.760	0.390	0.192	0.120	0.056

The data are plotted in Fig. 5 (Appendix).

(4) DETERMINATION OF BOD RATE CONSTANT AT DIFFERENT DEPTHS OF THE POND AT 25 DEGREES CENTRIGRADE:

Table 6

BOD Values and the Corresponding Days

	Sampling Point 6					
Days	1	2	3	4	5	6
BOD mg/l	30	48	65	70	76	84

Sampling Point 5

Days	1	2	3	4	5	6
BOD mg/l	31	46	59	60	68	71

Sampling Point 4

Days	1	2	3	4	5
BOD mg/l	31	47	65	73	84

Sampling Point 3

Days	1	2	3	4	5
BOD mg/l	35	52	72	79	89

Sampling Point 2

Days	1	2	3	4	5
BOD mg/l	39	50	61	68	78

For the determination of k by Fugimoto method, Y_{t+1}, the BOD exerted in (t+1) days is plotted against Y_t, the BOD exerted in (t) days. The data are plotted in Figs. 6 to 10.

APPENDIX

FIG. 1
5-D BOD Vs COD OF FEED SEWAGE.

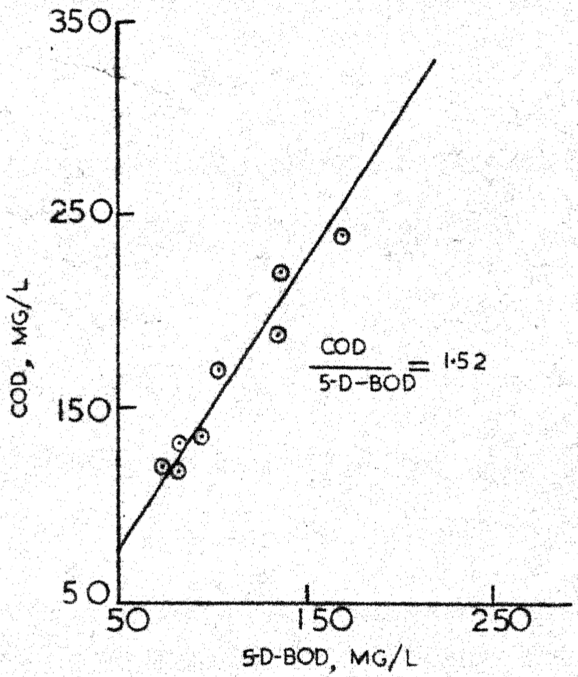


FIG. 2
STD CURVE FOR TOTAL PHOSPHATES AT 690 mμ ON "SPECTRONIC 20", LIGHT PATH 1CM.

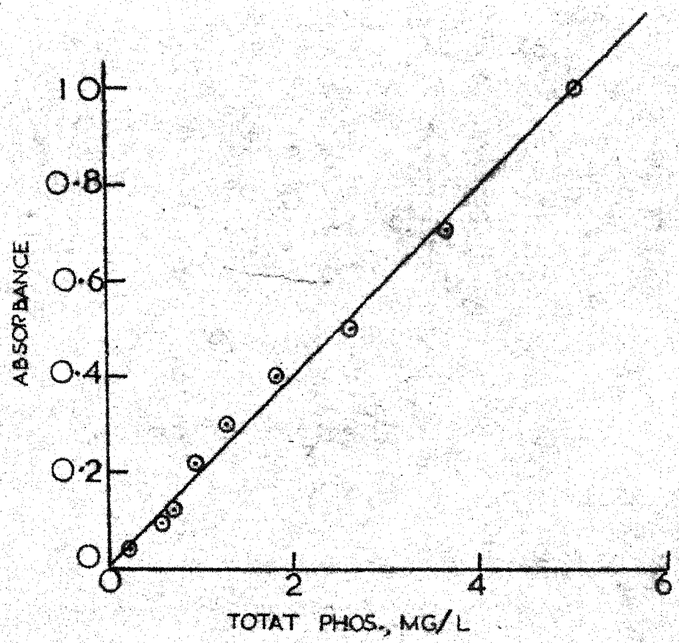


FIG. 3
STD CURVE FOR NH_3-N AT 430 Mμ ON "SPECTRONIC-20", LIGHT PATH 1CM.

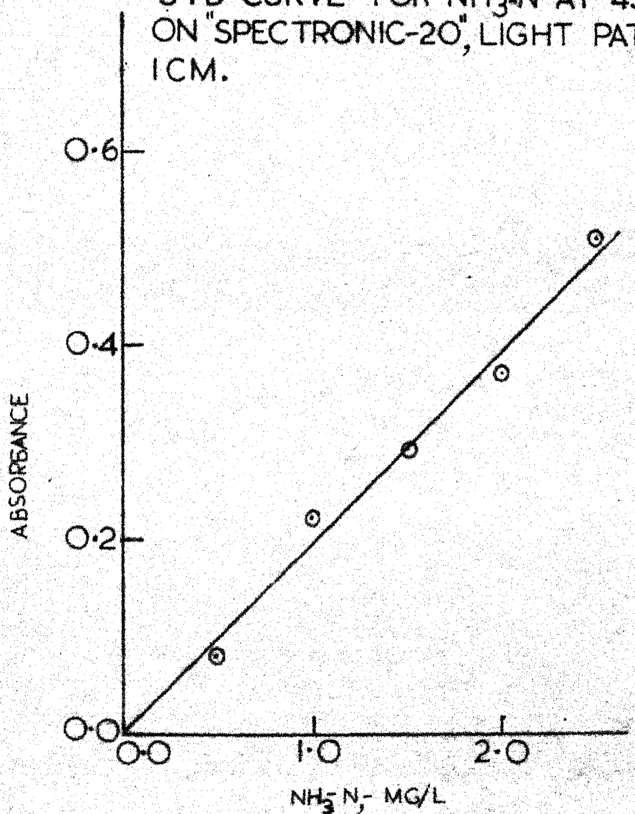


FIG. 4
DETERMINATION OF WAVE LTH FOR POND WATER ON "SPECTRONIC-20", LIGHT PATH 1CM.

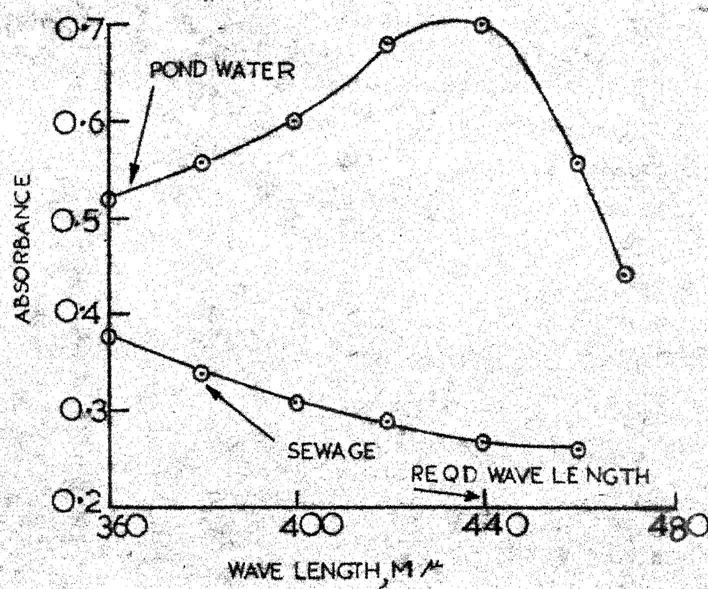


FIG. 5

STD CURVE FOR ALGAE CONC. AT 440Mμ ON "SPECTROTNIC 20" LIGHT PATH 1CM.

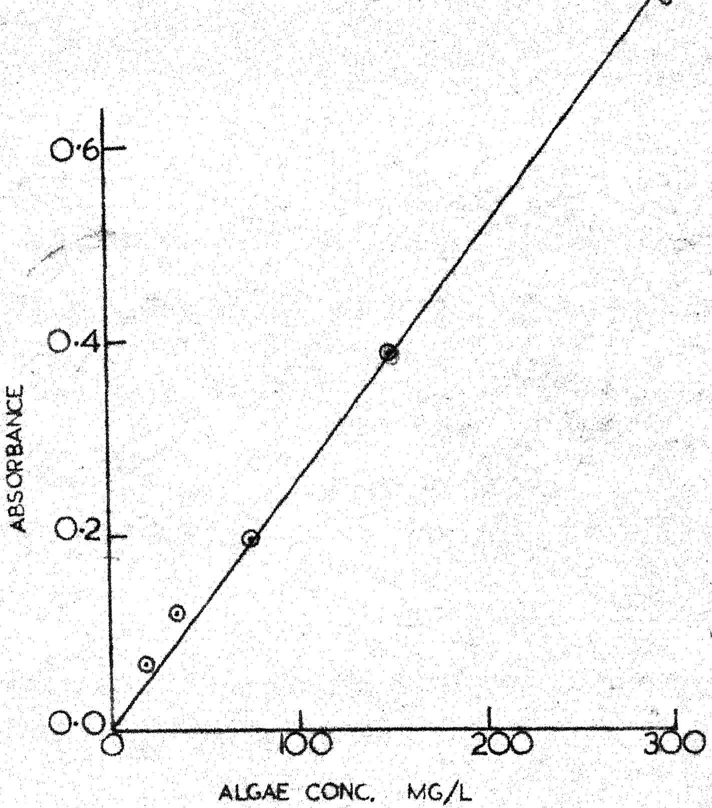


FIG. 6

DETERMINATION OF K. SAMPLING POINT 6, TEMP. 25° C (FUGIMOTO METHOD).

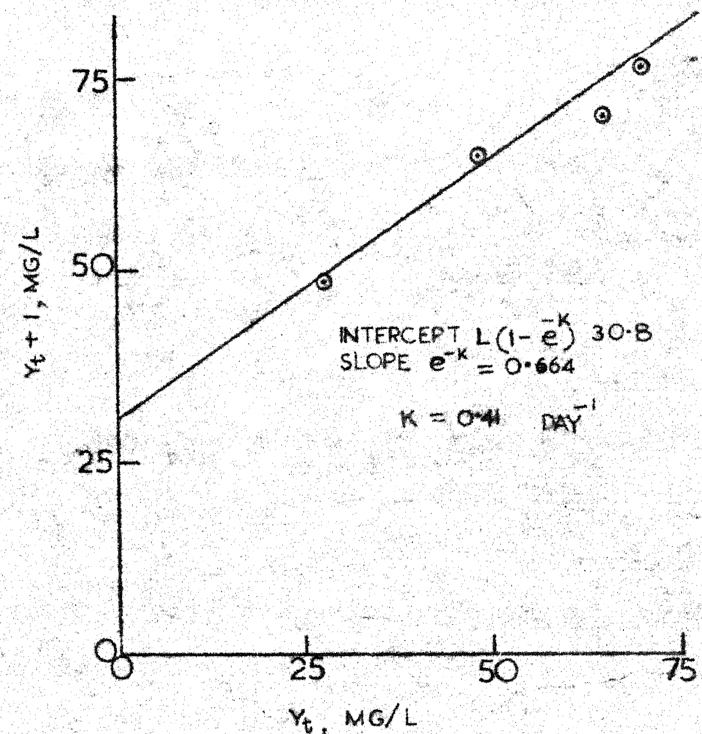


FIG. 7

DETERMINATON OF K. SAMPLING POINT 5, TEMP. 25°C (FUGIMOTO METHOD).

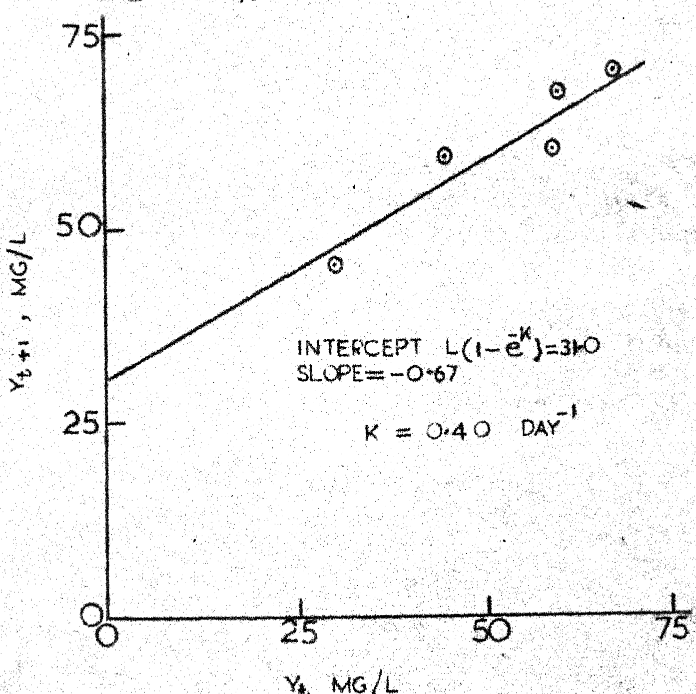


FIG. 8

DETERMINATION OF K. SAMPLING POINT-4, TEMP. 25° C (FUGIMOTO METHOD).

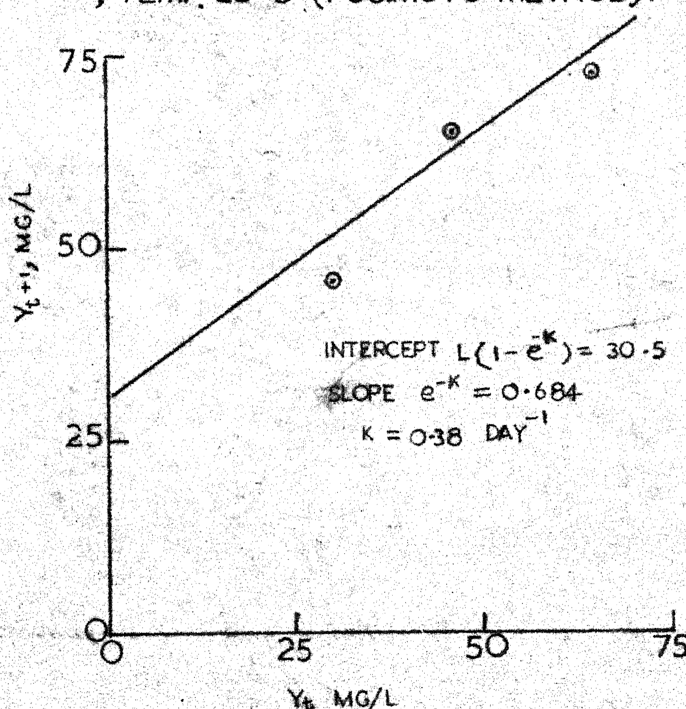


FIG. 9

DETERMINATION OF K. SAMPLING POINT 3. TEMP 25°C (FUGIMOTO METHOD)

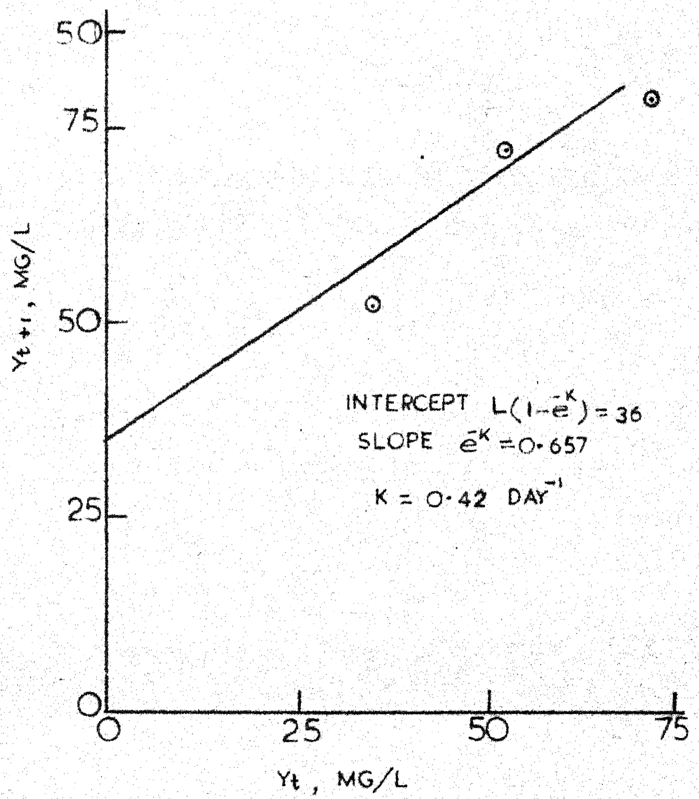
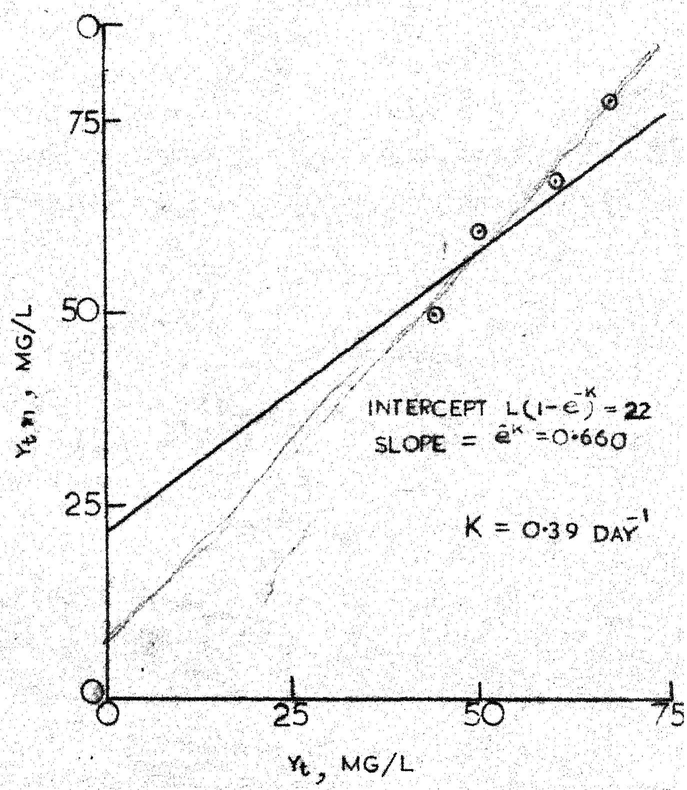


FIG. 10

DETERMINATION OF K. SAMPLING POINT 2; TEMP 25° C. (FUGIMOTO METHOD)



LIST OF REFERENCES

1. Edminston, F.E., "Fish Ponds for the Farm", Chas. Scribner, 1947.

2. Butler, M.A., "Irrigation in Persia by Kanats", Civil Engg., 3, 1933.

3. Sedgewick, W.T., "Principles of Sanitary Science and Public Health", Mcmillan, 1902.

4. Central Public Health Engineering Research Institute, Nagpur, "Oxidation Ponds" - a brochure, 1966.

5. Babbit, H.E., "Status of Stabilization Ponds", Proceedings, Symposium on Waste Treatment by Oxidation Ponds, Central Public Health Engineering Research Institute, Nagpur, 1963.

6. David, N.E., "Oxidation Ponds", ibid., 1963.

7. Barnes, G.E., "Oxidation Ponds for the Treatment of Sewage and Wastes", ibid, 1963.

8. Ludwig, H.F. et al, "Algae Symbiosis in Oxidation Ponds - I Growth Characteristics of E. gracilis cultured in Sewage", Sewage & Ind. Wastes, 23, 11, 1137, 1951.

9. Parker, C.D. et al, "Purification of Sewage in Lagoons", Sewage & Ind. Wastes, 22, 760, 1950.

10. Caldwell, D.H., "Sewage Oxidation Ponds - Performance Operation & Design", Sewage Works Journal, 18, 433, 1946.

11. van Heuvelen W., et al, "Sewage Lagoons in North Dakota", Sewage & Ind. Wastes, 26, 6, 771, 1954.

12. Hermann, E.R. et al, "Waste Stabilization Ponds - I Experimental Investigations", Sewage & Ind. Wastes, 30, 511, 1958.

13. Oswald, W.J. et al, "Photosynthesis in Sewage Treatment", Trans., Am. Soc. Civil Engg., 122, 73, 1957.

14. Oswald, W.J., "Fundamental Factors in Stabilization Pond Design", Proc. 3rd Conf., Biological Waste Treatment, Manhatten College, New York, 1960.

15. Oswald, W.J.; Goluke, C.G., Univ. of Calif. Inst. Engg. Research Series, 149, 1, 1959.

16. Lackey, J.B.; Smith, D.B., "Biological Treatment of Sewage and Industrial Wastes", Vol. I, Reinhold, New York, 1956.

17. Oswald, W.J.; Goluke, C.G., "Advances in Applied Microbiology", Vol. II, Academic Press, 1960.

18. McKinney, R.E., "Biological Treatment of Sewage and Industrial Wastes", Vol. I, Reinhold, New York, 1956.

19. Oswald, W.J. et al, "Studies in Photosynthetic Oxygenation", Univ. of Calif., Inst. of Engg. Research Series, 44, 9, 1958.

20. Hutchinson, G.E., "A Treatise on Limnology", Vol. I, John Wiley, New York, 1957.

21. Imhoff, K. & Fair, J.M., "Sewage Treatment", John Wiley, New York, 1940.

22. Oswald, W.J., "Light Conversion Efficiency in Photosynthetic Oxygenation", Ph.D. Thesis, Univ. of Calif., Berkeley, 1957.

23. Goluke, C.G., "Temperature Effects on Anaerobic Digestion of Raw Sewage Sludge", Sewage & Ind. Wastes, 30, 10, 1225, 1959.

24. Heukelekin, H., "Biological Treatment of Sewage and Industrial Wastes", Vol. II, Reinhold, New York, 1958.

25. Fitzgerald, G.P. & Rohlich, G.A., "Evaluation of Stabilization Pond Literature", Sewage & Ind. Wastes, 30, 9, 1213, 1958.

26. National Research Council, "Sewage Treatment at Military Installations - Summary and Conclusions", Sewage Works Journal, 20, 1, 52, 1948.

27. Allan, N.B., "General Features of Algal Growth in Sewage Oxidation Ponds", Publication No. 13, California State Water Pollution Control Board, 1955.

28. Silva, P.C. & Papenfuss, G.F., "A Systematic Study of the Algae of Sewage Oxidation Ponds", Publication No.7, State Water Pollution Control Board, Sacramento, California, 1953.

29. Oswald, W.J. et al, "Algae in Waste Treatment", Sewage & Ind. Wastes, 29, 4, 437, 1957.

30. Merz, R.C. et al, "Investigation of Primary Lagoon Treatment at Mojave, California", Sewage & Ind. Wastes, 29, 2, 115, 1957.

31. Oswald, W.J. & Gotaas, H.B., "Photosynthesis in Sewage Treatment", Jour., Sanitary Engineering,Division, Am. Soc. of Civil Engrs., 81, 686, May 1955.

32. Towne, W.W. et al, "Raw Sewage Stabilization Ponds in Dakota", Sewage & Ind. Wastes, 29, 4, 377, 1957.

33. Gloyna, E.F. & Hermann, E.R., "Algae in Waste Treatment-Discussion", Sewage & Ind. Wastes, 29, 4, 455, 1957.

34. Kinzey & Sharp, "Environmental Technologies in Architecture", Prentice Hall, 1963.

35. Neal, J.H. & Hopkins, G.H., "Experimental Lagooning of Raw Sewage", Sewage & Ind. Wastes, 28, 11, 1326, 1956.

36. "Standard Methods for the Examination of Water & Waste Water", 12th Edn., 1965.

37. Fugimoto, Y., "Graphical Use of First Stage BOD Equation", Jour., Water Pollution Control Federation, 36, 1, 69, 1964.

38. Myers, J. & Crammer, M., "Nitrate Reduction and Assimilation in Chlorella", Jour., General Physiology, 32, 93, 1948.

39. Aiba, S. et al, "Biochemical Engineering", Academic Press, 1965.

40. Herbert, D. et al, "The Continuous Culture of Bacteria - A Theoretical and Experimental Study", Jour., General Microbiology, 14, 601, Nov. 1955.